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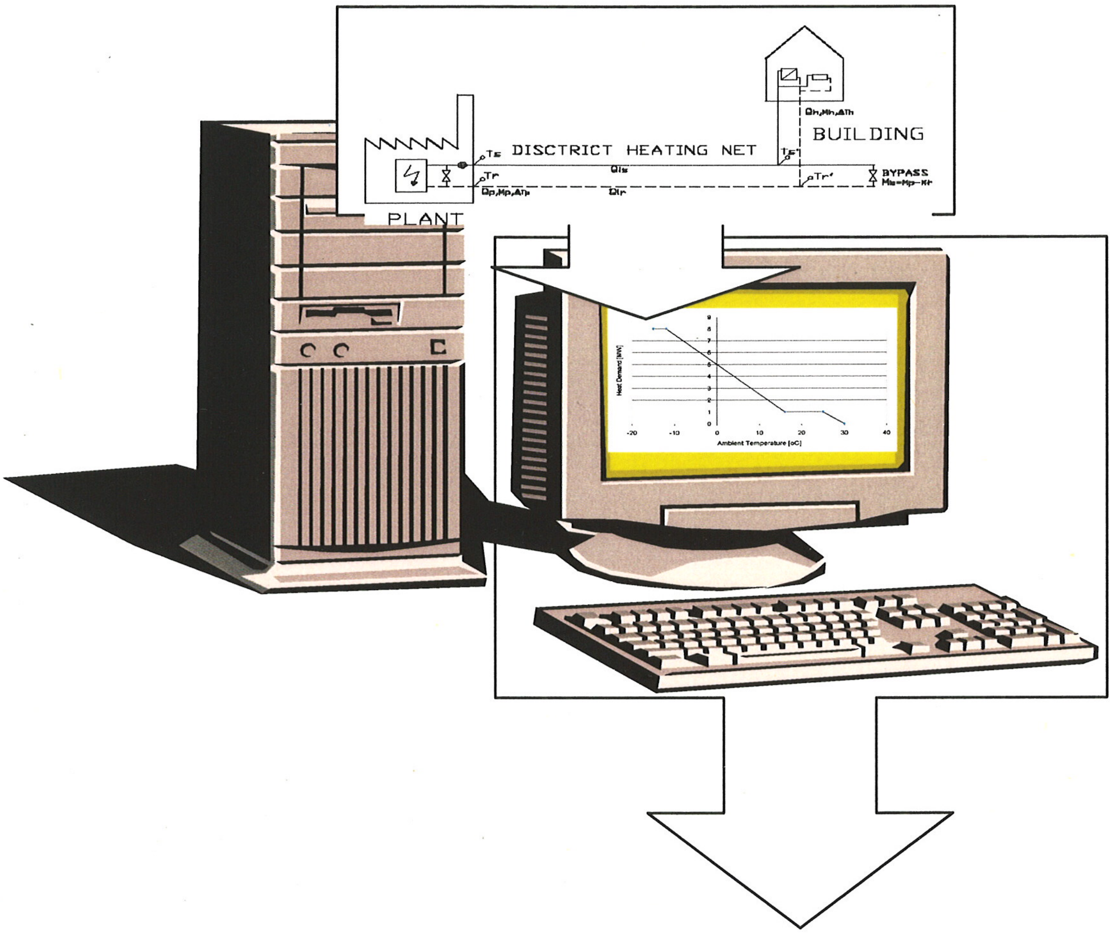
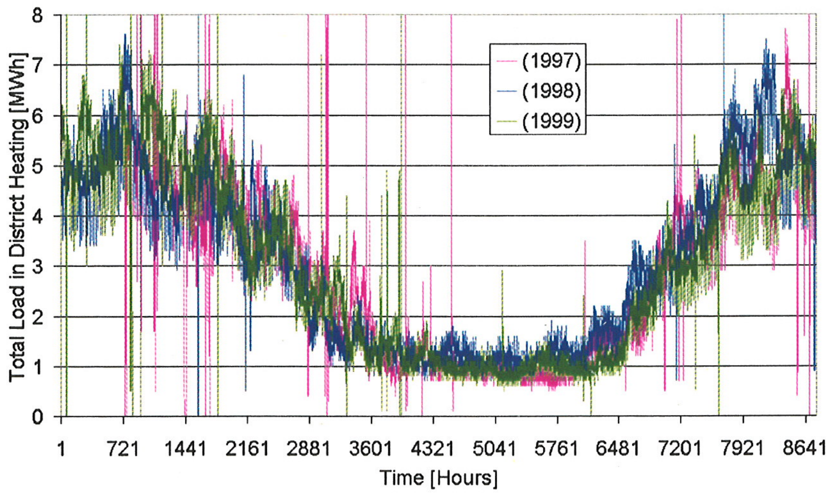
DEMAND MODELLING FOR CENTRAL HEATING SYSTEMS

ALFRED HELLER

DTU





REPORT

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DEPARTMENT OF BUILDINGS AND ENERGY
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IBE

PREFACE

The current text represents the first report in a series, finalising my research activities in attaining a Ph.D. degree in the field of "Large-Scale Solar Heating" at the Department of Buildings and Energy, Technical University of Denmark (DTU). Thanks to the Department of Energy Engineering for support regarding the district heating technology.

Framework for the current report:

The term "Central Heating Systems" cannot be found in literature, but seems relevant here. The term is introduced to gather a number of different heating systems, involving central heating production plants and some kind of distribution net. For large systems the term District Heating is applied. For small networks no English term is available. The German term "Nahwärme" is misrepresented by the terms "Block-Heating" or "Small district heating" (Dahm, J., 1999). They should rather be called something like "Local Heating Systems", similar to the mentioned German term.

The objective of the current report is to describe the demand side (consumers' demand) of such systems that has to be satisfied regardless of the heat source applied. Due to the lack of literature on the subject based on solar heating research, most inspiration is gathered from work in the field of district heating. These research publications had different aims and approaches, motivated by ensuring a high service level at a low price:

- Optimisation of plant design. Construction cost saving.
- Optimisation of plant operation. Operation cost saving.
- Service optimisation. Better services for the consumers.

Similar aims are the motivation for realistic modelling of central solar heating systems, the main research subject of the author.

Heat demands (loads) for complex large systems are studied the last decades, among other things to be able to optimise the design and operation of such systems. The literature is widely spread and the author could not find any comprehensive survey on the subject. Hence the attempt is made here to collect a large amount of material in one publication. This certainly implies a rather extensive, possibly confusing, mass of information, pressed together in one single report. I hope the result will at least be of help for readers to find an easier way through the literature jungle. I also hope that, by publishing work by others, interested readers can save time in finding the originals. In some cases the presented work is simply the first written version of commonly applied methods by colleagues. I feel that it is worthwhile publishing the methods for wider use and also for citation purpose, saving time in describing things again and again.

Acknowledgements:

The research was financed by a scholarship from the Technical University of Denmark under the Ph.D.-programme "Society, Planning & Technology". Thanks to DTU for the financial support and for the possibility of carrying out such a futuristic research project. Assuming that there is a need for central solar heating systems in the future, coming generations will be grateful for this contribution.

SUMMARY

Most researchers in the field of heat demand estimation have focussed on explaining the load for a given plant based on rather few measurements. This approach is simply the only one adaptable with the very limited data material and limited computer power. This way of dealing with the subject is here called the top-down approach, due to the fact that one tries to explain the load from the overall data. The results of such efforts are discussed in the report, leading to inspiration for own work. Also the significance of the findings to the causes for given heat loads are discussed and summarised.

Contrary to the top-down approach applied in literature, a here-called bottom-up approach is applied in this work, describing the causes of a given partial load in detail and combining them to explain the total load for the system. Three partial load "components" are discussed: 1) Space heating. 2) Hot-Water Consumption. 3) Heat losses in pipe networks. The report is aimed at giving an introduction to these subjects, but at the same time at collecting the previous work done by the author.

Space heating is shortly discussed and loads are generated by an advanced simulation model. A hot water consumption model is presented and heat loads, generated by this model, utilised in the overall work. Heat loads due to heat losses in district heating are given a high priority in the current work. Hence a detailed presentation and overview of the subject is given to solar heating experts normally not dealing with district heating.

Based on the "partial" loads generated by the above-mentioned method, an overall load model is built in the computer simulation environment TRNSYS®. The final tool is then employed for the generation of time series for heat demand, representing a district heating area. The results are compared to alternative methods for the generation of heat demand profiles. Results form this comparison will be presented.

Computerised modelling of systems involving fluid flows brings along a problem called "numerical diffusion". This subject will be discussed in much detail. The objective of doing so is to find a solution that is generally applicable for the simulations of flows in e.g. solar collector tubes, thermal tank models and so on.

In some cases the implementation of heat loads involves assumptions to meteorological parameters. In this report two methods representing such data are discussed: 1) Simple function models. 2) Climatic reference data sets. The methods will here be examined and discussed.

To estimate the reality of generated heat demand "profiles", measurements from a district heating case are used for comparison. No comprehensive validation is carried out here. The comparison with the measurements shows that the generation tool is not able to represent the real system. However, the tool can be applied for the modelling of new settlements where the heat load is not known and must be estimated by other means.

A rather comprehensive section with discussion and conclusions closes the report.

RESUME PÅ DANSK

De fleste forskere der beskæftiger sig med emnet forbrug i store, centrale varmesystemer har fokuseret på at kunne forklare forbruget på værket ud fra meget overordnede målinger på det varmeproducerende værk. Der var simpelthen ingen anden vej, bl.a. på grund af manglende viden om systemerne og manglende computerkraft. Ved forskellige teknikker har man analyseret de målte data og er kommer frem til forskellige modeller. Denne måde at arbejde med emnet er her kaldt "top-down approach", da man forsøger at forklare forbrugets årsager ud fra hele forbruget. Der gives i rapporten et overblik over det arbejde der er lavet om emnet og de resultater der er fundet herved.

I modsætning til den ovenfor nævnte top-down måde at gøre tingene på, anvendes i det foreliggende arbejde den omvendte fremgangsmåde, her kaldt "bottom-up". Ved at forklare de enkelte forbrugskilder i detaljer forsøges at kunne beskrive det overordnede forbrug for et helt centralvarmesystem. Tre forbrugskilder - som egentlig er det omvendte af en kilde, nemlig en årsag til forbrug – bliver nævnt: 1) Varme til opvarmning af bygninger. 2) Varme til varmtvandsforbrug. 3) Varmetab i fjernvarmeledninger. Formålet hermed er at give læseren en inledning til emnet, men også at opsamle det omfattende materiale om emnerne i en enkelt offentliggørelse.

Opvarmning i bygninger er et af hovedemnerne på vores Institut og kunne fylde en hel rapport for sig selv. Her gives en oversigt og henvises til inspirerende litteratur. Tilsvarende gives inspiration til arbejde med varmtvandsforbrug. Her gennemgås dog i detaljer en model der anvendes i det efterfølgende værktøj til simulering af varmeforbrug. Det tredje emne, varmetab i fjernvarmeledninger, fylder en hel del i rapporten, da det ses som et emne der er mindre kendt af bygnings- og solvarmefolk. Da forfatteren arbejder med disse emner, er der behov for at bygge en bro mellem de involverede emner. Det er forsøgt i denne rapport. Varmetabet i en fjernvarmeledning kræver at man kan bestemme varmefordelingen og strømninger i rører hensigtsmæssigt. Det viser sig dog at dette er ret vanskeligt for computermodeller. Der er forsøgt mange løsninger ofte på basis af nogle fysiske og af fagfolkene forståelige principper. I den foreliggende rapport er det forsøgt at finde en generel løsning på numerisk basis, da denne ville være meget mere generelt anvendelig og kunne løse problemet for alle tekniske fænomener af denne art. Derfor er der anvendt en del plads til gennemgang af problemet og mulige løsninger heraf.

På baggrund af gennemgangen af enkelte "forbrugskilder" opbygges en model til simulering af varmeforbruget i store, centrale varmesystemer. Hertil bruges et computerværktøj, TRNSYS, som anvendes i stor grad af solvarmefolk.

Modellering af varmeforbrug kræver kendskab til de vejrmæssige forhold der påvirker systemet. I denne rapport gennemgås to metoder til simplificering af de klimatiske forhold: 1) Simple matematiske udtryk. 2) Referencedatasæt, baserede på målinger over lang tid.

For at kunne se om resultaterne fra det opbyggede computerværktøj til generering af forbrugsdata giver brugbare resultater, er resultaterne sammenlignet med tre års målinger fra et fjernvarmeværk i Marstal på Ærø. Der er ikke gennemført en egentlig validering af værktøjet. Herudover er resultaterne sammenlignet med resultaterne fra simple metoder. Vi finder desværre at værktøjet, i den givne version, ikke gør arbejdet bedre end de bedste simple metoder. Alligevel ses der et behov for sådanne værktøjer til anvendelse ved estimering af forbrugsdata for barmarksprojekter.

Rapporten afsluttes med et ret omfattende afsnit med diskussion og konklusioner.

Abbreviation and Computer Program Names

The following abbreviations and names of computer programs can be found in the text:

Abbreviation	Description
CHS / CHP	Central Heating System/Plant
DH	District Heating
LSSH	Large-Scale Solar Heating
CSHP	Central Solar Heating Plant
CSDHP	Central Solar District Heating Plant
CSBHP	Central Solar Block Plant
CSHPSS	CSHP with Seasonal Thermal Storage
CSHPDS	CSHP with Diurnal Thermal Storage
CSHPxS	CSHP without Thermal Storage
IEA	International Energy Agency
SHC	Solar Heating and Cooling programme under IEA.
SH	Space Heating
DHW	Domestic Hot Water
HWP	Hot-Water Preparation
DL	Distribution Loss, heat loss in pipe networks
WDL	Week-day Load, load dependent on week-day

Name of Computer Program	Description
TRNSYS®	Computer program for dynamic simulations. (Klein, S. A. and many others, 1996)
PRESIM®	Interface program for TRNSYS® for system simulation.
Issibat®	Interface program for TRNSYS® for system simulation.
PREBID®	Interface program for TRNSYS® for building simulation.
BID®	Tool program for TRNSYS® for building simulation.
MATLAB®	Mathematical software by MathWorks®. http://www.mathwork.com.
SIMULINK®	Simulation environment for MATLAB®.

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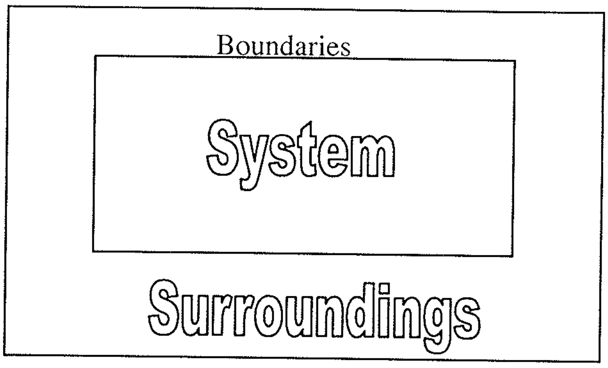
1. INTRODUCTION

Central heating plants or systems service an often large number of consumers with heat for different purposes, e.g. space-heating and hot-water consumption. The heat is produced centrally and distributed through a given pipe network.

The individual consumers' demands are varying a lot and a simple heat demand pattern is not available. However, research is done to describe some common patterns of the heat demand for central heating systems. In this work an attempt is made to collect work presented in literature and hereby to give readers a reasonable comprehensive survey of the representation of heat demands, here also called loads.



The author is working with large-scale solar heating technologies. Due to the fact that in Denmark such systems are connected to district heating networks, it is necessary to be able to predict and model heat demands for central heating systems. Working with solar heating technologies normally involves a rather well-defined consumer definition and belonging heat demand. For small systems the demand consists of the hot-water consumption of typically a few people only, (Qin, L., 1998). For hybrid-systems, partial supply for space heating is added to the load. Heat losses related to these heat demands are to be superimposed. Examples can be found in (Eriksson, L., Zinko, H., and Dahm, J., 1998) and (IEA SHC Task 26, 1999). For large solar block heating systems the complexity of the demand pattern grows due to the involvement of many types of consumers. Especially for large-scale solar heating systems connected to district heating, the pattern can be very complex and involve many different consumers, e.g. single and multi-family housing, office blocks, industries and so on.In the following the simplified assumption is made that the distribution network and heat production plant can be seen as a system with a well-defined boundary to its surroundings.

The system can be a district heating plant or a central solar heating plant.

The surroundings are the consumers, the ambient weather and some technical installations.

The surroundings influence the system through the boundaries.

<u>The objectives of this work are</u>

- **to present a general model approach for the realistic representation of the influences of the surroundings on the central heating systems.**
- **to collect published material on the subject in a more comprehensive manner and thereby to fill part of the gap in the literature of thermal system modelling.**
- **to give an example of such a model as a starting point for others. The resulting model will be utilised in the following work by the author.**

1.1 Context of the report

The report is divided into three main parts, where the first part is mostly general, collecting the general descriptions, theories and models, applicable to any kind of heating system.

The second part describes the method of computer simulation and a concrete implementation of the general model in a computer simulation environment, TRNSYS. Hence the scope of this second part is less general and can be skipped by readers interested in the general load modelling.

In the third part of the report, a real case is examined. Measured and simulated heat loads are compared and load models classified by the ability of predicting this load as realistic as possible.

Part 1 - Theory and Method:

To give an introductory survey of the methods for load modelling, some widely used methods are presented in section 2, spreading from simple techniques to more advanced ones. The top-down approaches are presented and discussed in section 3 giving the reader the basic understanding of heat demand modelling for central heating systems. In the following section 4, the partial causes for heat load demands are introduced. Space-heating and hot-water preparation are discussed shortly and sources for further readings surveyed. A particular hot-water demand model is presented in detail. The presentation is strongly focussed on the heat loss modelling of district heating pipes, due to the fact that this subject is not widely known yet, but very central for realistic modelling of central solar heating systems, the main topic of the author. The individual causes for heat demands are often dependent on input parameters such as meteorological data. Some simplification models for such input data are presented and compared in section 5. Among other things simplified expressions for ambient temperature, ground temperature and cold-water temperature are presented and the reference data sets for Denmark compared in detail, leading to recommendation for the application of such simplifications and data sets. To make the results accessible, data sets are placed on the Internet for downloading.

Part 2 – Dynamic Modelling:

In part 2 the attempt is made to apply the findings from Part 1 into a computer simulation model. Before doing so, some relevant general topics are discussed in section 7. A short comment is placed to dynamic modelling and the time-dependency of a given physical phenomenon in section 7.1. Special attention is paid to the modelling of flow in pipes in section 7.2, showing to be a rather complex subject in numerical modelling. Many attempts are made to solve the problem by physical means. Such models are typically closely related to the given application, e.g. a thermal storage tank. The goal in the current presentation was to abstract from physical means and find a numerical solution to the numerical problem. Hereby the results are more generally applicable for e.g. pipe flow, cavity flow, flow in absorber pipes of solar collectors, flow in storage tanks and much more. The implementation of the heat load model is shown in section 8, starting with the implementation of the given heat causes and a final collection to a general heat load modelling tool.

Part 3 – Case Study:

To evaluate the final heat load-modelling tool, measurements from a case study are used to compare the results from the tool. After an introduction of the case, some analyses are made on the measurements in section 9. Hereby findings from literature could be compared with own results. In section 9.2 the measured and simulated results are compared, followed by a comparison of the computed results by other techniques to estimate heat load demands in section 10. A discussion of the case and a summary of conclusions for the case are given in section 11.

The report ends with a rather extended section with discussion and conclusions of heat load modelling.

PART 1 - Theory and Method

2. Heat Demand Modelling Approaches – A Survey

Heat demands/loads are mostly very complex. This complexity is growing strongly for optimised systems, where the overhead of the system is minimised and hereby no reserves are available to counteract fluctuating effects. It is claimed in this work that over-sizing of systems must be eliminated in the future to avoid waste. Consequently future engineering claims higher complexity in the solution of technical systems, here central heating systems. To be able to design and operate such systems without "overhead", the load pattern must be known as precisely as possible. In Part 2 an attempt is made to define a detailed load estimation tool.

In the current section a survey is given, spreading from simple to more complex model approaches for load estimation. Simple models involving a few calculations only. Complex methods require computer power due to the many computations necessary. It is worthwhile mentioning that the increased complexity demands increased knowledge for modelling. Hence the application of a given technique is dependent on the knowledge available at a given stage.

The load/demand for a given central heating system consists of a summary of loads that can be ascribed to a sink, e.g. the demand for hot water. In the following two attempts to work with heat load modelling will be discussed. One attempting to describe the individual sink by the analysis of heat load data for a whole plant/system, here called top-down approach. The other doing the opposite of finding the total heat load by describing the individual sink in more or less detailed manner, here called bottom-up approach. The former will be discussed in section 3 and the latter in section 4. Some simplifications for the modelling of the surroundings of a system are discussed in section 5.

The accuracy of a given method will be discussed in Part 3 where the presented models are compared in a real world case. The generality of the application of the methods is more complex and will be discussed in the final sections.

2.1 Extreme simple load models

For very rough estimates, yearly values for the load and a percentage distribution of this total value over the twelve months, is a commonly used method. See Figure 1 for a fictive example. If the monthly distribution is not known by measurements, some statistical distribution can be applied. If using measured monthly values, the method gives surprisingly realistic load values. This can be explained by the fact that the measured data represents the total system including all the known and less known contributions to the total load. The main strength of the method is that no prior knowledge from individual load components is necessary. The method can be applied for simple comparison with more complex load models.

→The method should only be used if no other way can be found.←

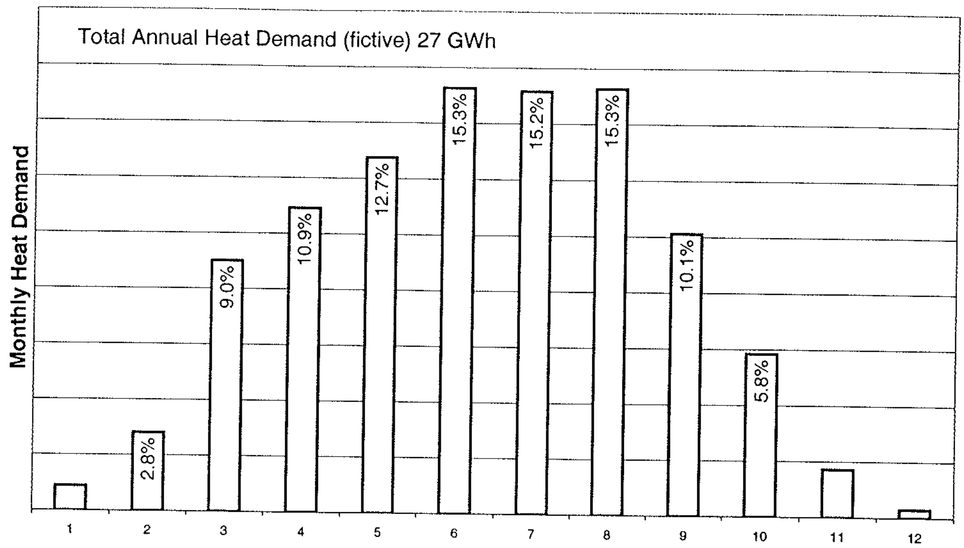


Figure 1 Annual heat load and monthly distribution in percentages for a fictive case.

2.2 Energy characteristics / Signature models

Another very simple method for the description of heat loads is called energy characteristics or energy signature. The method is described and applied by (Aronsson, S., 1996) for the correction of measured district heating loads.

Simple functions are applied for the description of any kind of relevant influence on the system, e.g. the function plotted in Figure 2.

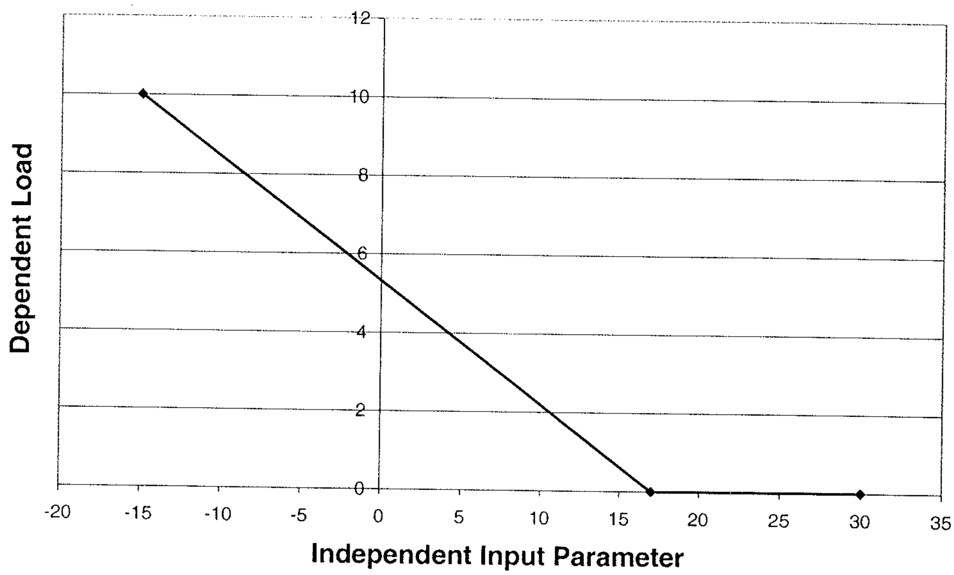


Figure 2. A typical function applied in energy signature models describing the dependency of the load on a given influence (input parameter).

In the example, Figure 2, a stepwise linear function is applied. This could be the dependency of the load on the ambient temperature. Such curves can be obtained by plotting measured data and finding a realistic approximation. Also back-box approaches can be applied to find such dependencies.

Defining such functions for any relevant input parameter, the method could be extended to reproduce all the load components separately. Non-linear functions could easily be introduced to reflect such dependencies. However, the linear version is found in literature only.

The energy characteristic method is simple, but demands more knowledge of the given system than the previous method. However, in many cases a "general" characteristic valid for many cases is applied. This is recommendable only if no detailed knowledge is available.

Note: (Aronsson, S., 1996) states that the method reflects the inertia of the mass in buildings, district heating and other large thermal capacities, when using average values of "long" intervals, e.g. weekly or monthly values for the determination of the function coefficients/parameters.

→The method is very simple and can be applied if other means are not available. See also final remarks at the end of the report.←

2.3 Normalisation of measured data

The above methods assume measurements of load data from a given period. Each season has an individual pattern. To make data from different years comparable two methods can be applied – the degree-day correction presented and applied in (Aronsson, S., 1996), (Lawaetz, H., 1987) and (DANVAK, 1999) and the energy signature correction, presented in (Aronsson, S., 1996) and discussed in the previous section.

The degree-day (alt. degree-hour) method is based on meteorological measurements. The degree-day value, GD_p, for the actual period is calculated as the number of observations where the average ambient temperature is below a given threshold, in the Danish case 17 degrees Celsius. The time length of an observation is typically an hour or a day (hence the naming). By summing the values over the period, a degree-day value is determined for this period. This is done for a "normal" period, GD_n. Hereby the heat load for an actual period, Q_p, is then normalised by the expression $Q_n = Q_{sh} \frac{GD_n}{GD_p}$, where Q_{sh} is part of the load that is directly affected by the ambient temperature, mostly the space-heating load only. Other load components, such as domestic hot water preparation, are normally not degree-day normalised. This is often done by normalising 80% of the load.

The threshold value of 17°C is chosen to reflect the need of heating for residential buildings, heated to an indoor temperature of 20-21°C by accounting for the dynamic influence of the thermal capacity of the building. It must be mentioned that this is a simplified version of the degree-day methods applied in Denmark, where degree-values are set to zero for warm periods.

→Note that the method leads to erroneous results for systems with other thermal dynamics. Hence it is expected that the method will lead to wrong results for low-energy buildings and must be adjusted for these purposes.←

Some attempt to enhance the method is made by correcting the degree-period values by the solar irradiation and wind.

→The method is very simple and shows the best results for simple methods. See also Part 3 and final remarks at the end of the report.←

2.4 Steady-state models

The above methods can be classified as a kind of lookup-table. The following methods are basically different. Here the system is simulated based on any kind of model/representation.

The simplest simulation method is based on steady-state assumptions, where temperatures and flow rates are kept constant for short or long time periods. Assuming the constant conditions for a given period, the corresponding heat load is estimated by well-defined and standardised calculations. Loads can be estimated for the whole system as described in section 4.3.2.5.

Note: Similar methods exist for building heat load modelling and other parts influencing the load of a central heating system.

2.5 Back-Box Methods

If one is not able to find any theoretical description of a given phenomenon the input-output (stimuli-responds) method is applied in many scientific fields. Here a so-called black-box is coupling the input in a manner that the output is representing the results as expected. The theory for such black-box methods is rather advanced and readers are referred to e.g. (Ljung, L., 1987).

2.6 Dynamic modelling

Dynamic modelling is different from the above methods by the fact that the method can handle changing surroundings to a given system. In the steady-state method the surrounding is simplified to constant values. This is actually also the case for most dynamic methods, but with the difference that the present interval where an ambient influence is assumed constant is very short.

There are two basic paradigms for building dynamic models - stochastic and deterministic. Deterministic models are often seen as more realistic and to give more insight into the matter. On the other hand, deterministic models cannot always reproduce the real world by satisfactory accuracy. In such cases the basically deterministic models are supplied with some stochastic parameter estimates of even stochastic parts of the models. This is a common approach to escape lack of knowledge for a given system.

2.6.1 Stochastic modelling

Almost all the models that are mentioned in this text could be classified as deterministic models where the load components are well-behaved patterns that can be described by theories based on mathematics and physics. However, load patterns for heating systems show some more arbitrary load parts that cannot be handled by the deterministic models and must be described by stochastic (based on statistics) models. An example of such arbitrary behaviour, the simultaneousness of user loads, is for instance many people taking a shower at the same time. The idea is to base a given load model on some statistic probability of a given occurrence, combination of occurrence and so on. For further reading on such models, see for instance (Sejling, K., 1993), (Madsen, H., Pálsson, H., Sejling, K., and Søgaard, H. T., 1990) and (Pálsson, H., 1993). An example will also be presented for hot-water loads in Part 2.

2.6.2 Deterministic modelling

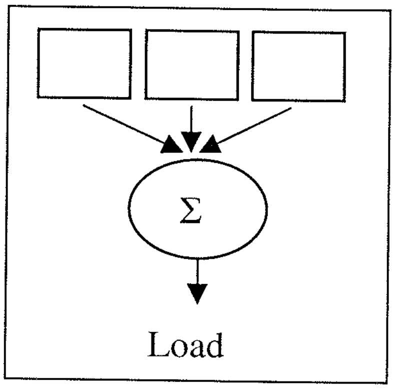
Deterministic models are implementations of physical theories often described in mathematical terms, e.g. natural laws and empirical models described as expressions and equations. In some cases, e.g. the heat losses in buildings, the model can include multi-dimensional heat transport phenomena described by partial differential equations. For long-term simulations such approaches would need an enormous amount of computer power. To simplify the task, the equations are reduced to ordinary differential equations by discretising the problem in space, leading to a set of equations dependent on one space dimension and the time only. Such system models are solved by dynamic simulation, where the load is found for very short periods, e.g. minutes or hours, assuming the boundaries for the system constant in these time intervals. The approach is central for the current work and will be discussed in detail below and applied in Part 2 of this report.

3. General Load Models – The Top-Down Approach

The overall procedure described in this section will here be called the Top-Down Approach. This approach is found in literature by researchers aiming to explain the heat load for a given system by analysing measured loads for a whole central heating system. The motivation for this research was to be able to define a simple model including some few predictable parameters that would represent a given heat load. Hereby one would be able to control central heating systems in a more appropriate way.

In this section a general description of the heating demand, published by (Werner, S. E., 1984), will be summarised. The resulting model was inspiration for some following work by (Aronsson, S., 1996), (Larsson, G., 1999) and others. The resulting basic model will be presented and discussed here and some findings for the significance of partial terms will be discussed. The model will then be used as a guideline in the development of a dynamic load model in Part 2.

3.1 The Basic Model



In the general load model the assumption is made that loads are a composition of additive elements that are based on physical theory. The composition elements are not correlated. This assumption introduces a certain error into the model that must be kept in mind.

The model can be generalised to the form

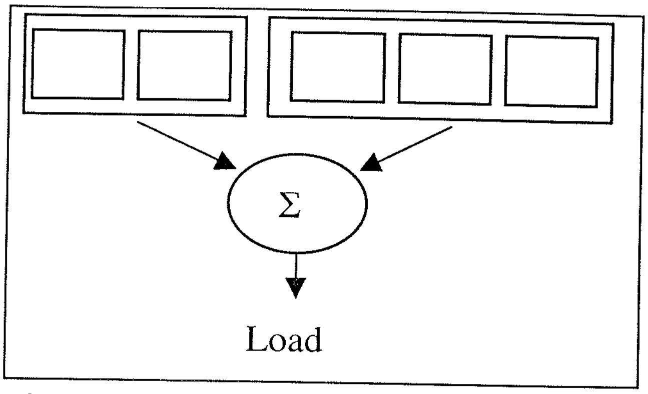
$$Y = \sum_{i=1}^{n} X_i \qquad (1)$$

where
- Y is the dependent model variable (the heat load),
- X_i independent model variable element (e.g. wind speed),
- i number of the actual element (1,2,..,n),
- n total number of independent elements that shape the dependent variable.

(Werner, S. E., 1984) presents a survey of model descriptions of the general kind followed by a specification of a more general applicable model involving model coefficients, β_i. These coefficients are used to adjust the independent model variable, X_i, in expression (1), resulting in the following adjusted model:

$$Y = \sum_{i=1}^{n} \beta_i X_i \qquad (2)$$

The puzzle is now to identify the relevant components and then in one or another way to determine the model coefficients for the individual load components. For the determination of the model coefficients, also called parameters, most authors adopt a statistical method, "multi-regression analysis". Alternatively one could adopt time-series analysis or a neural network (Note: Neural network can be implemented very similar to multi-regression analysis methods). Based on such analysis on measured data, typically hourly data, the cited authors were able not only to estimate the parameter values but also the significance of the load components and hereby to decide the relevancy of the components.



As mentioned Werner represents a number of independent components and finds the corresponding coefficient based on measurements. Werner also proposes that similar elements could be collected to so-called load components. (Aronsson, S., 1996) chooses this approach by combining components with similar influencing input parameters to abstract groups. For at typical district heating system we find the following four load components that together shape the total heat load:

- space heating (SH) for buildings
- domestic hot water preparation (HWP)
- distribution loss (DL)
- additional workday loads (WDL).

The analytical work for this approach is similar to the above, namely to find the corresponding coefficients, but for fewer elements compared to the Werner-model.

In section 0, the individual load components will be discussed in detail, except for the additional workday load that is related to large and atypical consumers connected to the central heating system. This type of loads cannot be modelled in a general manner and must be based on measurements on the given case.

3.2 Significance of load components

The individual heat load elements or components have various impacts on the total heat load profile. Based on daily heat load observations covering between 5 and 11 years of six Swedish district heating systems, (Werner, S. E., 1984) estimates the significance of the individual load components. In short the findings are that space heating (≈60%) and hot-water preparation including heat losses in the installations (≈30%) are the dominating factors for load modelling for residential areas. The district heating losses account for a minor contribution of approximately 6-8%. It is also analysed in Werner that the HWP varies dependent on weekday variations (user behaviour dependent on the weekday) and monthly variations (cold water temperature variation during the year). The hot-water preparation showed a significant seasonal dependency with higher hot-water consumption in winter than in summer. Significant parameters were identified to be the ambient temperature, the solar radiation and the wind speed. These parameters show influences on more than a single component model. Hence component models are correlated and the claim of independence between additive components not justified.

According to Werner, load simulation is sufficiently accurate when including space-heating, hot-water preparation and heat loss from the DH-system.

(Aronsson, S., 1996) carried out a study, where 50 substations of the Gothenburg district heating were monitored with 15-minute measurement intervals over a period of 18 months. HWP accounts, according to this study, for 11-15% of the total load only, independently of building type, size and age. This is significantly lower than the estimation by Werner. Aronsson shows correlation between space-heating and hot-water preparation. Due to the model formulation by Werner, which claims independence between elements, such correlation cannot be modelled.

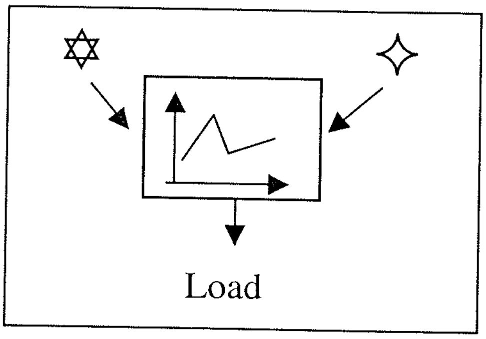
→Note: The discussed resulting error will especially be accentuated for low-energy housings and optimised systems. This must certainly be considered if modelling futuristic systems.←

Table 1 Estimation values for heat load components found in literature.

Load Component	Significance estimations in %		
	Werner	**Aronsson**	**Bøhm**
Space heating (SH) for buildings	60		
Domestic hot water preparation (HWP)	30	11-15	
Distribution loss (DL)	6-8		>20
Additional workday loads (WDL)	Rest		

The summary in Table 1 shows very wide variety of estimation for the significance for the individual load components. This shows, among other things, that different systems show very different significance. The Bøhm estimation will be commented below.

A study by (Larsson, G., 1999) was focusing on the district heating load as a boundary condition for his own modelling, similar to the current work. The main subject in Larsson was the fluid dynamic behaviour of DH systems and the modelling of this phenomenon. Unlike the prior authors, building on physical models, Larsson applies a black-box method. Applying a regression analysis on daily average values for the heat power load of the Gothenburg district heating, Larsson investigated the heat load pattern based on input parameters instead of components. Seen from this perspective the approach seems similar to an energy characteristic method presented in the section before.



Larsson found that the ambient temperature is the most dominating parameter for load simulations. The second important parameter is connected to time, the hour of the day and weekday, in other words the user behaviour and time-dependency of control systems. Such type of dependencies of the load on time can be periodic in hour, day, month or year. Another relevant parameter for load modelling is the solar radiation, followed by wind speed. By analysing figures by Larsson we find that the amplitude of the influences corresponds to the following share rate in total load for the mentioned influences. See Table 2:

Ambient temperature 83.1%, temperature of the cold water 8.8%, solar radiation 7.7% and the influence of wind 0.2%. From this study we can conclude that simulations based on ambient temperature, cold-water temperature and solar radiation is sufficiently correct.

Table 2 Estimation values for heat load components found in literature.

Input Parameter	Significance estimation in %
Ambient temperature	83
Cold-water temperature	8.8
Solar radiation	7.7
Wind	0.2
Humidity	< 0.1

The studies quoted above find the parameters defining the DH-system model for a given case, based on statistical regression analysis of measured daily data over a given period. There are two handicaps attached to this approach. 1) Normally one does not have this kind of data in the required sampling frequency. 2) The presented source did not describe how they handled influences having impact on more than a single component and parameter. Moreover the methods are rather demanding. A more applicable method is presented by (Bøhm, B., 1999b). Here the author bases his estimation of heat losses for district heating on the measurements of at least two large systems in Copenhagen and finds much higher heat losses in percentages for Danish systems than estimated by Werner. The high value can be explained by the very low "density" of user demand in relation to the length of the district heating net. In Denmark, also single-family areas are covered by DH, due to the very high heat overflow from the production of mainly electricity production (co-generation).

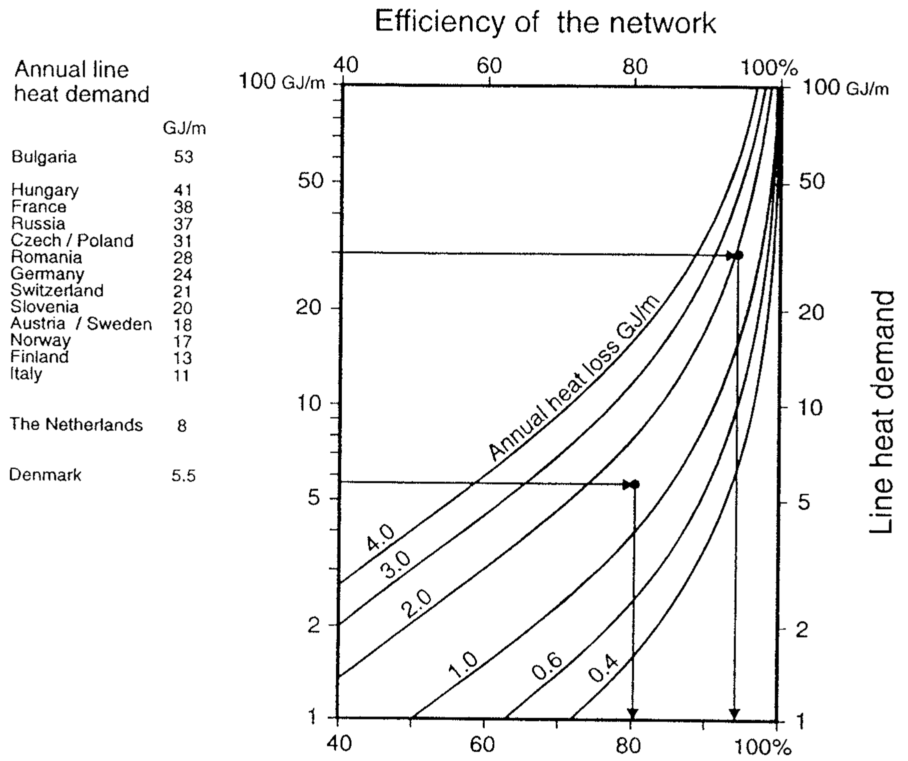


Figure 3 Annual efficiency of a district-heating network as a function of annual line heat demand. Inserted are annual line heat demands for European countries. Source: (Bøhm, B., 1999a).

In Figure 3 the efficiency of a DH-network is plotted on the apses, spreading from 40 to 100% efficiency. On the ordinate axes the line heat load is plotted on a logarithmic scale. The line heat load is the total annual heat load divided by the length of the pipe net, two values that are simple to find. Central heating systems with high line heat loads tend to have lower heat losses than systems with low line heat loss ("energy density"). This seems also reasonable from a logical point of view. The curves in Figure 3 can now be used for an estimation of the heat loss per metre of pipe in the DH-system, knowing the age, design etc. of the system - all information known to the system operators. Hence the method is easy to apply and leads to realistic heat loss estimations.

Note: The annual line heat value for Denmark is very low. Knowing that the insulation level for the Danish DH-systems is reasonably high, this supports the finding of "low density" for the systems.

Concentrating on a single curve we find that for increasing line heat load, the efficiency of the system is growing. More demand on a short DH-net leads to few heat losses and high efficiency. This seems reasonable. Comparing the plots for different annual losses per metre of pipe, we find the efficiency decreasing with increasing heat loss.

→As we will see in the following, the Bøhm approach is recommended due to the complexity of the real world phenomenon.←

→The figures and values presented above are very much dependent on the given system. No comprehensive study could confirm the values. Hence the reader must take the values with care. However, one can use the values for first estimates and assumptions if no other values are available.←

4. Load Components – The Bottom-Up Approach

In the previous section 3 research is presented for the systematic description of heat demands in district heating, the Top-Down Approach. Three variants were cited: (Werner, S. E., 1984) led to a set of load elements, describing the different causes for a given load profile. (Aronsson, S., 1996) collected the load elements with similar input parameters to four load components; space heating, domestic hot water preparation, distribution losses and additional workday loads. (Larsson, G., 1999) was tackling the problem from the other side, the input parameter side, and tried to find correlation between these input parameters, e.g. the ambient temperature, to the load.

In this section a basically opposite approach is applied, namely to find the load by detailed modelling of the cause for heat demand and hereby to find the total heat demand by connecting the individual partial demands. This can be done by deterministic or by stochastic procedures as reported by (Madsen, H. and Schultz J.M., 1993) or by deterministic models as presented in the current work.

Here the partial loads are investigated by analysing literature on the cause that leads to the load, e.g. the consumers, the buildings etc. This approach can be done for the above-mentioned "components" – for the individual additive elements, abstract load components or even for the independent input parameters. Combinations are also possible.

The objective of this survey is to give a starting point for readers that are interested in more detail in the given component models and to give a background for the models applied in Part 2.

4.1 Space Heating

Space heating ensures a proper thermal comfort in buildings by maintaining the indoor temperature at a desired, uniform level and serving for proper admission of fresh air. In some regions cooling must be included, which is not a dominating factor for the typical central heating system in Denmark.

A space-heating model is normally represented by building models. Such models must, in one way or another, deal with the causes for thermal effects sketched in Figure 4. Please note that the sketch is taken from a study on atria, which explains the "strange" building design. However, the complexity of space-heating modelling is still valid.

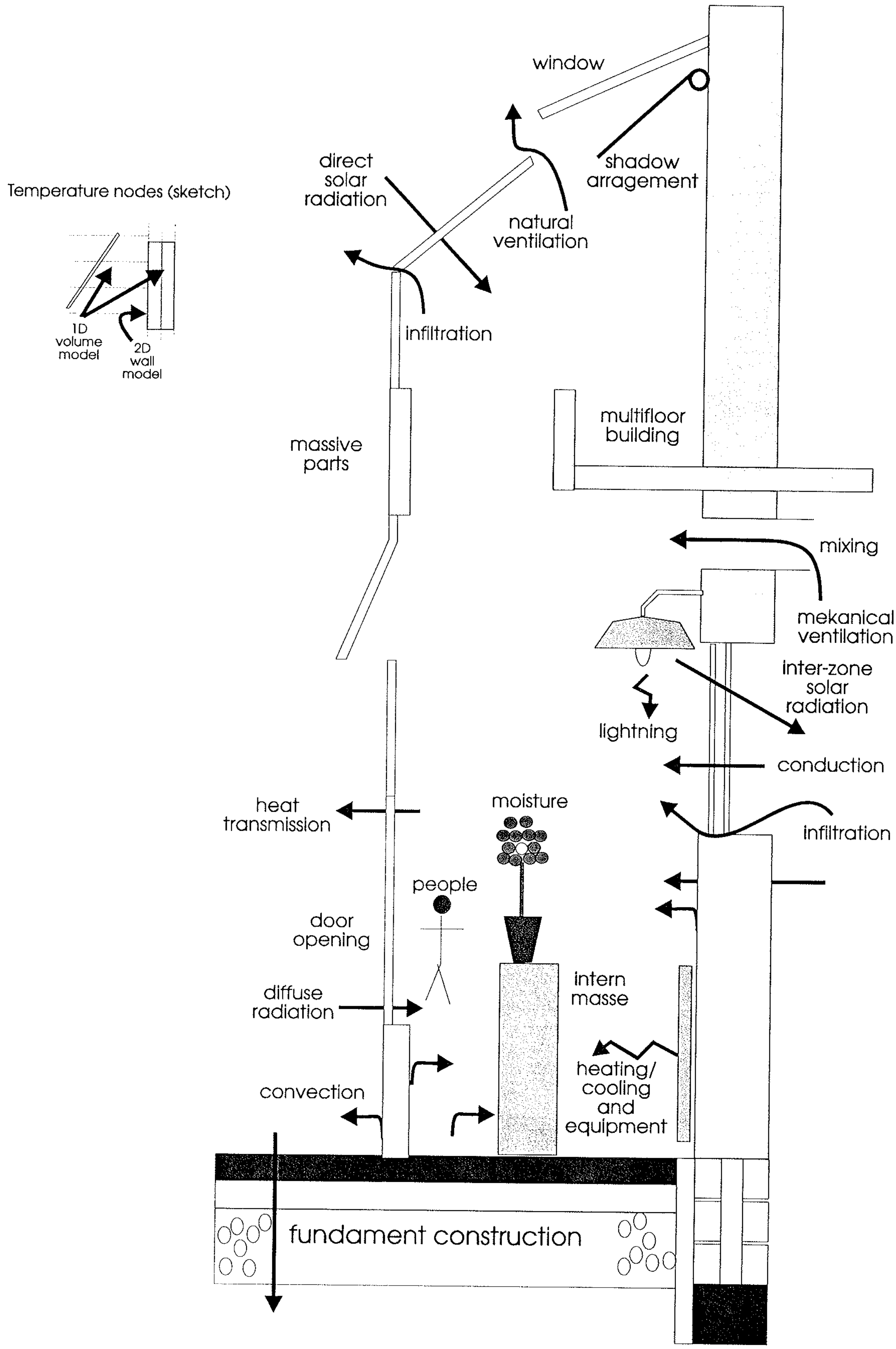


Figure 4 Sketch of relevant causes, leading to space-heating demands.

As one can imagine the task is not trivial. Space-heating models are numerous, spreading form very simple to dynamic and multi-dimensional models. A comprehensive survey is not possible here.

Heat-loss computations, for Danish conditions, can be based on work by the Danish Building Research Institute in (Aggerholm, S., Zachariassen, H., Christensen, G., Olufsen, P., Clausen, V., and Pedersen, P. E., 1995) or norm texts as in (Dansk Standard, 1986) and related amendments,(Dansk Standard, 2000d), (Dansk Standard, 2000c), (Dansk Standard, 2000b) and (Dansk Standard, 2000a). See also European Norm (EN 832) for simple computations.

The simplest models estimate the space-heating load based on a few component parts, implemented as node models. Here the temperatures in the building are computed by heat and mass balances and hereby the heat load can be found. Some models include a single zone for the whole building, other model each room individually. Basically, the whole building or a single zone is, in node-models, represented by one or a few temperature nodes, connected by thermal resistance, the component parts. In a 2-node model, the first node represents the steady-state heat losses, including air-borne heat losses, and the second node "takes care of" the dynamic response of the thermal mass. More sophisticated models include more than one single node for the representation of masses, such as walls. This is necessary for the realistic estimation of e.g. passive solar buildings. Radiation models for the estimation of influences on the heat load, e.g. solar radiation and radiative heat exchange between building surfaces, can also spread from simple single-node models to very advanced ray-tracing models. In the first representation the radiative heat exchange is transformed into temperature changes in the given building. In the latter all surface temperatures and illuminations are computed into detail.

Note that even very complex computer models are built upon such simple node schemes and assumptions, including more component parts in more sophisticated implementations.

From literature the following component parts are selected to be most significant for space-heating modelling:

- Heat losses through building envelope by transmission.
- Heat losses by natural and forced ventilation and infiltration.
- Solar heat gain through windows and passive solar installations.
- Internal gain, by e.g. electrical apparatus, inhabitants and hot-water preparation.

As an alternative to the node methods above, (Werner, S. E., 1984) recommends a regression model based on indoor, ambient temperature, wind speed and solar gain. The transient thermal response is represented by a response factor method in an explicit manner. The resulting four parts for the space-heating load are then: 1) A part for the steady-state transition loss. 2) A rather simple part for the transient response of the transmission loss (heat capacity of the building materials). 3) A part for the influence of the wind on the natural ventilation. 4) A part representing the influence of the solar radiation, split into a contribution by the direct and a diffuse solar gain. Thereby Werner finds a method with explicit formulation of the heat load for the space heating.

(Werner, S. E., 1984) estimates heat load to account for approximately 60% of the total heat load for district heating systems. Hence the proper modelling of this load component is decisive.

(Aronsson, S., 1996) states that space heating is correlated to the age and type of the building (e.g. residential buildings, office block), but surprisingly not with the size of the buildings. The latest observation is not very realistic, due to the fact that space heating is dominated by heat loss through the building envelope which again is strongly dependent on the size of the buildings. This example demonstrates a weakness of a black-box approach that leads to unrealistic results.

To be able to convert the delivered heat from a distribution net to comfort heat, some kind of installation must be involved, radiators, heat exchangers and so on. This subject is among others disputed in (Dahm, J., 1999). The load component for space heating consists therefore of the heat compensation plus the efficiency losses of a given installation. The latter is, among many others, described in (Qin, L., 1998), (Eriksson, L., Zinko, H., and Dahm, J., 1998) and was repeatedly subject for work by the author of (Paulsen, O., 1989).

We can conclude from this very short presentation of space-heating modelling that the level of complexity must be chosen from case to case. But there is no doubt about the fact that space heating is the main cause of heat demands in central heating systems in Nordic countries.

4.2 Domestic Hot Water Preparation

According to (Werner, S. E., 1984) the share of the hot-water preparation load and related heat losses in the local distribution system, discussed in section 4.3.1, accounts QUOTEfor approximately 30% of the total load in district heating systems. Hence this influence on the total load must be modelled realistically.

Heat load for domestic hot water for single family and multi-family buildings can be estimated based on the Danish Standard (Dansk Standard, 2000e).

Spread work has been made to determine the demand of hot water. (Qin, L., 1998) and (Mazin, M. and Maleki, M., 1995) give some starting points for load estimation in Denmark. No final models are presented, except from the fact that:

→Danish, (ibid.) German (Mack, M., Schenk, C., and Köhler, S., 1998) and Swedish (Aronsson, S., 1996) measurements show similar patterns and a distinct over-dimensioning of DHW-installations, based on standards. Hence reconsideration of standards would be relevant.←

Domestic Hot Water (DHW) loads depend on a large range of factors, e.g. number of residential units, heat losses in the installation itself, intersection of building components due to the installations, the number of inhabitants and their behaviour. In many cases it has been tried to explain the behaviour by social parameters such as age, sex, social ranking and more. Measurements are carried out for a number of cases, spreading from a few residential units to large areas. The measurements show large fluctuations and variations between different objects, users etc. A load model based on all these varying influences would be unadoptable. Hence mean-values and simple models are in general applied to reflect average daily, weekly, monthly and yearly variations in demand defining the resulting load pattern.

(Qin, L., 1998) summarises hot-water loads measured in Denmark that vary between 70 and 270 l per day for single-family houses and 50-160 l/day for apartment building units. (Mack, M., Schenk, C., and Köhler, S., 1998) present a study of German measurements that show variations of hot-water demands between 20 and 45 litres per person at 60°C, which is in perfect correspondence with the findings in Qin.

For small systems the term domestic hot water (DHW) is applied. In the studies on district heating systems the term Hot Water Preparation (HWP) is preferred for the including of e.g. hot-water demands for industrial purposes.

HWP demands show a seasonal pattern due to varying hot-water consumption with higher loads in winter than in summer periods. This results in a superposition of total loads for central heating systems.

Similar seasonal pattern can be related to the supply temperature, the cold-water temperature as discussed in section 5.3. This water temperature varies according to (Aronsson, S., 1996), (Mack, M., Schenk, C., and Köhler, S., 1998) and (Yang, L., 1994) in a smooth sinus-formed curve, as presented in Equation (17) with coefficient values found in Table 7.

The user behaviour is certainly a very important factor for HWP-loads. The diurnal pattern shows two peak load periods; one in the morning and one larger peak in the evenings. The weekday has an impact on the load, due to the different behaviour in workdays and weekends. Most authors reported this pattern.

According to (Aronsson, S., 1996) HWP consumption is correlated, in the case of district heating systems, to building age, size and building area to be serviced. This seems not to be the case for residential buildings. The dependency between HWP demand and the age is also found by (Mazin, M. and Maleki, M., 1995) up to the 70ies, when the demand drops due to the oil crisis. A later drop is reported by Aronsson possibly based on the fact that sanitary installations in resent years tend to save resources. Hence parameters reflecting this correlation should be included if the system includes non-residential areas.

→Again we find an "unknown" dependency that must be recognised for futuristic systems, underlining the fact that optimised systems must be handled with more care than done in the past for less optimised systems allowing "overheads", waste and over-sizing.←

4.2.1 The IEA SHC Task 26 Model – A stochastic approach

Under the International Energy Agency (IEA) programme for Solar Heating and Cooling (SHC), Task 26 "Solar Combisystems", a stochastic approach is introduced, covering the statistical distributions and probabilities of the hot-water demand from single families to a large number of involved persons. The model is reported by (Jordan, U. and Vajen, K., 2000a). For a single or a set of representative households, a load profile is generated from the individual profiles for the HWP-load. The resulting profiles can then be superpositioned to profiles with still realistic profiles for up to ca. 70 consumers. For larger systems additional profiles must be generated. Especially for large central heating systems the diffusion of an individual behaviour is of importance.

The method is basically as follows: For the generation of the heat load, four categories of loads are included: A) Small draw off (washing hands). B) Medium draw off (dish washing). C) Bath and D) Shower. Each category is presented by a Gauss-distributed curve describing the interrelation (the probability) between the flow rate and the number of draw off, building together the overall draw-off probability distribution. For the four categories the key values presented in Table 3 are assumed for the Austrian, Swiss and German participants in the co-operation.

*Table 3 Key-values for the Hot-Water consumption model by Jordan, applied in IEA SHC Task 26 work. * Once a week.*

Type		**Unit**	**Single-Family Draw Off**			
Maximum energy draw off		Wh	5680			
Medium load volume per day		l	200			
Total water demand per year		l	70200			
Description	**Units**	**A**	**B**	**C**	**D**	**Total**
Flow rate	l/min					
Duration	min					
Incidents per day		28	12	0.143*	2	
Standard deviation		2	2	2	2	
Volume per load	l	1	6	140	40	
Volume per day	l	28	72	20	80	200
Portion of total		0.14	0.36	0.10	0.40	1.0

Moreover the following influences on the HWP are applied:

- The probability that a given situation occurs is defined by $P(\tau) = P(year) * P(weekday) * P(day) * P(holiday)$. Hence yearly, weekly, daily and weekday influences are taken into account by the following means.
- The probability of the demand during the year can be described by a sinus-function with an amplitude of 10%.
- The probability in relation to the weekday is described for each category. In the current implementation all categories, except the category "bath", are gathered under a single distribution. The bath category is handled by its own distribution due to the high probability of taking bath in the weekends. Resulting distribution during the weekdays is: Medium load for all days: 100%. Monday-Thursday: 95%. Friday: 98%. Saturday: 109% and Sunday: 113%.
- For the daily distribution profiles are defined for each category, defining together a profile with two peaks in mornings and evenings with constant demand during the day and no demand in the night.
- The holiday distribution is defined by dates. For defined holidays, the probability distribution for the hot water draw-off is reshaped for the given day.

As an example, the daily load due to hot-water consumption in a single-family house is sketched in Figure 5.

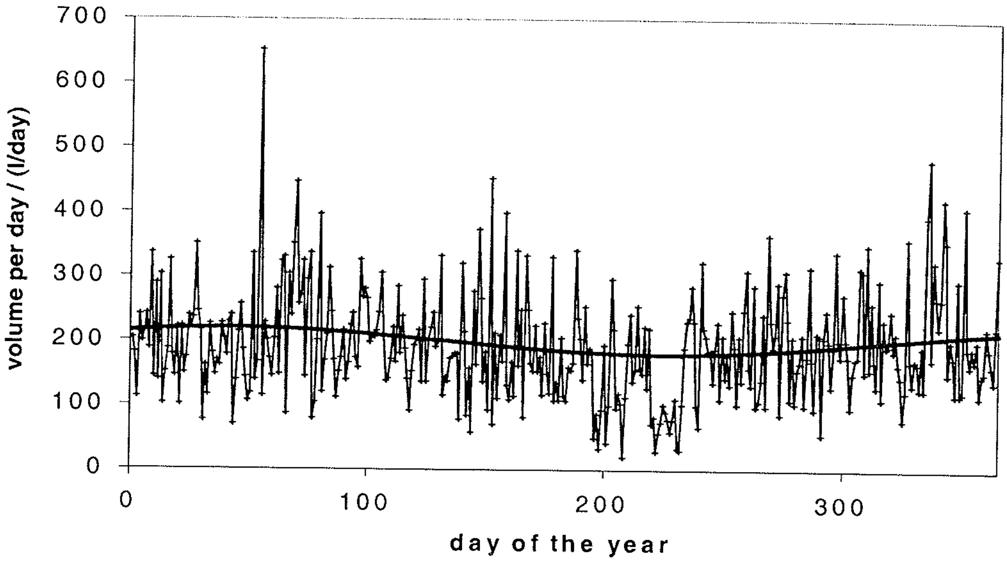


Figure 5 Hot water draw off for a single-family house based on the Jordan algorithm and the key-values described above. Source: (Jordan, U. and Vajen, K., 2000a).

We find that the method generates a time-series for the hot water draw-off for a single family, a building complex or combinations hereof.

4.3 System Heat Losses

Two main causes of heat loss are included in the current presentation, pipe heat losses in the building supply net and heat losses in the district heating distribution net. The estimated heat loss from the distribution net is by (Werner, S. E., 1984) estimated at 6-8% and by (Bøhm, B., 1999b) at around ¼ of the total heat load. Hereby there is no doubt that circulation losses are to be modelled realistically to obtain a realistic total load model. Above the heat losses in the net, additional heat losses are connected to the substations connecting the distribution and the supply network, see (Yang, L., 1994) and (Dahm, J., 1999). The subject is not discussed in the current work. Circulation heat losses in buildings are presented in (Qin, L., 1998). DH heat losses are discussed extensively in literature.

4.3.1 Heat Losses in the HWP Distribution and Circulation Net

The consumption of hot water causes heat losses in the pipe network, due to 1) the losses due to transporting the medium to the consumers. 2) losses due to circulation which is applied to ensure high temperature at any point of the network at any time.

Literature on measured heat losses in circulation is rare, hence uncertainties are very large. Reports by (Svendsen, B. and Carlsson, P. F., 1995), based on one year measurement on a four-storeyed, multi-family block with 67 residential units, show that heat losses due to circulation can be up to 3 times the demand for hot water. Similar high results are reported based on measurements on an educational building by (Esbensen Consultans, 1991). (Boye-Hansen, L. and Furbo, S., 1995) report monthly values for circulation heat losses between 80 and 90% of the hot-water demand for a 44 residential unit, three-storey, row-housing area. A similar circulation loss, close to 100%, is found by (Kristensen, F., 1995). Even losses in the range of 200-400% are found in recent monitoring cases. Such systems are not representable and can be ignored here. In general the assumption is made that heat losses due to circulation are between

50 and 100% depending on the age of the system, the insulation level and the length of the distribution pipes. German and Swedish results seem to be much lower, lying between 10 and 50% in Sweden, (Dalenbäck, J-O., 2000) and 15-25% in Germany, (Vajen, K., 2000).

A proposal for the modelling of hot-water supply network in the buildings is put forward in (Qin, L., 1998). Readers interested in the dynamic net modelling are referred to this work. Similar inspiration can be extracted from the following section on district heating network modelling.

4.3.2 Heat Losses in District Heating Net

Literature of modelling of District Heating Losses is very extensive. Searching for references (Bøhm, B., 1999a) is a good starting point. In this section some basic background for the heat loss modelling for central heating network is presented, followed by some simple steady-state models, leading forward to some more dynamic models. For the models in detail and numerical aspects related to dynamic models, the reader is referred to part 2 of this report.

4.3.2.1 Overall district heating net modelling

The district heating net consists of large numbers of heating pipes, which must be represented in a given model. Hence it is central to find a realistic model for the very complex structure. It is certainly possible to describe a net with all its details. This is however not a realistic scenario, among others due to lack of information and resources. The complexity must therefore be reduced. Reduction procedures are proposed in (Bøhm, B., 1998), (Pálsson, H., Larsen, H. V., Bøhm, B., Ravn, H. F., and Zhou, J., 1999) and (Larsson, G., 1999). Any reductionor simplification will lead to loss of precision. It is the task of modellers to find a compromise, which is not a trivial task.

A very general approach for system reduction is known from electric analogy methods, where e.g. thermal systems are modelled by electrical circuits. Here a system of three nodes connected in a fourth central node can be reformulated by a triangle with three nodes only. Readers are referred to basic schoolbooks in electric and computational analogy theory for further reading on the subject.

(Pálsson, H., Larsen, H. V., Bøhm, B., Ravn, H. F., and Zhou, J., 1999) investigate so-called equivalent models where the net is successively reduced to less complex structures. The results of these models were then compared with the results of a very complex model. The authors report two alternative procedures for the reduction: 1) Ignoring parts of the net from the small pipes up to the larger ones. 2) Reducing the net based on logical considerations, such as e.g. the area around a large single user. By examining the response of a reduction in terms of deviation in temperature return to a DH-plant, the researchers were able to estimate the precision of the equivalent models. The most relevant result of this investigation for the current work is that the complexity of a net can, by applying a proper reduction procedure, be reduced from e.g. 50 branches to approximately 10 without severe loss of accuracy. The error in return temperature to the plant is less than 2 K. Reducing the net to even fewer branches leads to decisive loss of accuracy.

→This must be kept in mind when we look at single branch net representations in the following. Here, according to the cited work, the accuracy lies in the best case at approximately ±15%.←

(Larsson, G., 1999) presents an alternative approach to the above simplification of DH-nets based on hydrodynamic considerations for the simplification. The approach has shown astonishing precision for three presented cases. The following reduction procedure is reported:

1)The branch of a DH-system is reduced to one single point at the ramification of the pipes. Hereby the hydrodynamic influence of the branch is still realistically modelled.

2)To compensate for the missing thermal influence of the removed branch, the thermal capacity is assigned to a single virtual "load-point".

→For all simplification methods presented above, the procedure is either poorly documented or not easy to apply for others in the given stage. Hence other procedures must be found until better documentation is presented.←

A very simple and applicable method for the net reduction is presented by (Bøhm, B., 1998) and (Bøhm, B., 1999a):

1)The DH-network is reduced to two pipes.

2)The fluid volume in the DH-system must be the same for the real DH-system and the equivalent model.

3)The diameter for the pipe is found based on documentation material on, or knowledge about, the net as average.

4)Applying insulation thickness corresponding to the pipe diameter found by common dimension practice.

We found above that such a representation cannot give accuracy better than 15% for heat loss simulations in the best case.

4.3.2.2 *Basic assumptions for heat loss models for distribution networks*

Heat loss computations for district heating nets are basically carried out as described in e.g. the Danish Norm (Dansk Standard, 1994) for buried pipe couples, cited in section 4.3.2.3. The models include the following heat transport phenomena, describing the heat loss from transport fluid to ambient and the heat transport between the heat pipes:

- Convective heat transfer by the fluid due to mass flow in the pipe.
- Convective heat transfer from fluid to the pipe.
- Conduction through piping material, steel, insulation and casing.
- Conduction through the ground.
- Convective and radiative heat transports on the ground surface.

Models are obtained by governing heat and mass balance equations for the different involved parts. The most advanced models solve the problem by Partial Differential Equations in two or three dimensions, typically solved by Finite Element Methods. Most models simplify the domain to a one-dimensional problem described by either Ordinary Differential Equations or analytical expressions. According to (Bennonysson, A., 1991), such models can be categorised into fully dynamical and pseudo-dynamical methods, whereas the former solved the pressure, flow and thermal differential equation simultaneously, and for the latter the thermal equations are solved by assuming the others to be steady for short time intervals. Hereafter some of the most important subjects for simplifications that underlie the, in this work, presented methods are:

- The three-dimensional problem for heat loss from pipes is simplified by dividing it up into a problem describing the heat transport in the flow direction and one in a plane perpendicular to the flow direction.

- The transport in the flow direction is mostly described by a number of segments, nodes, discussed in Part 2.
- It is assumed that there exists an undisturbed ground temperature somewhere near the pipe. This assumption is discussed by (Bøhm, B., 1999a) in detail.
- A finite (small) volume can model the ground surrounding the pipe couple representing the response of the ground around the pipe.

The presentation of methods for calculating heat transports connected to buried district heating pipes is divided into methods assuming steady-state conditions and dynamic methods that will be described shortly in the following. Before going into detail with the calculation methods, some basics, common to most of the methods, will be presented in the following. After going through the Norm for the computation of heat losses in the next section, a simplified model schema is discussed in section 4.3.2.4, where a complete distribution network is represented in one single pipe couple. This simplified model is then applied and demonstrated for simple steady-state computations in section 4.3.2.5 and later in this work for dynamic simulations in Part 2.

4.3.2.3 The Danish Code for heat loss calculations (DS 448)

In the Danish Code, (Dansk Standard, 1994) normative descriptions connected to heat loss calculations in district heating systems are given. These descriptions and calculations are adopted by most of the following methods.

The heat power in W for a mass flow can be calculated by

$$Q = \dot{m} c_p \Delta T \tag{3}$$

where $\dot{m}$ is the mass flow rate of the heat transport in kg/s, c_p the specific heat capacity of the transport medium in kJ/(kg K) and ΔT the temperature difference of the transport in K.

The total heat loss from the distribution pipe couple can be calculated from the expression

$$Q_{l,tot} = Q_{ls} + Q_{lr} = 2(U_1 - U_2)\left[\frac{\overline{T}_s - \overline{T}_r}{2} - T_g\right] \tag{4}$$

where $Q_{l,tot}$ is the heat loss in the distribution heat pipe net in [W],
$Q_{l,s}$ heat loss in the supply heat pipe in [W],
$Q_{l,r}$ heat loss in the return heat pipe in [W],
U_1 heat transfer coefficient from DH pipes to surroundings in [J/(m K)],
U_2 heat transfer coefficient between the two DH pipes in [J/(m K)],
$\overline{T}_s$ average temperature of the supply pipe line in [K],
$\overline{T}_r$ average temperature of the return pipe line in [K],
T_g ground temperature in [K], which under code conditions is 8.8°C.

For symmetrical pipe layouts the heat transfer coefficients from piping to ambient, U_1, and between the two pipes, U_2, are found to by

$$U_1 = \frac{R_g - R_i}{(R_g - R_i)^2 - R_h^{\,2}} \quad \text{and} \quad U_2 = \frac{R_h}{(R_g - R_i)^2 - R_h^{\,2}}. \tag{5}$$

where R_g is the thermal insulance for the ground in [m^2 K / W],
R_i is the thermal insulance for the insulation material in [m^2 K / W],
R_h is the thermal insulance between the two pipes in [m^2 K / W].

The overall heat loss can be found by $U_{tot} = U_1 - U_2 = \dfrac{1}{R_g + R_i + R_h}$.

The insulance for the ground can be obtained by the expression

$$R_g = \frac{1}{2\pi\lambda_g} \ln \frac{4Z}{D_e} + R_{\alpha e} \tag{6}$$

where λ_g is the thermal conductivity or the ground normally set to 2 m K / W,
D_e outer diameter of the pipe casings in [m],
$R_{\alpha e}$ surface thermal insulance at the pipe case surface to the ground in [m^2 K/W].

The value of Z, the corrected depth of the piping, is found by the expression $Z = z + R_0 \cdot \lambda_g$, where z is the physical depth of the piping in metres, and R_0 the surface thermal insulance of the ground surface, normally set to 0.0685 m^2 K /W.

The thermal insulation of the insulation material around the pipe is given by

$$R_i = \frac{1}{2\pi\lambda_i} \ln \frac{D_c}{d_y} + R_{\alpha c} \tag{7}$$

where λ_i is the thermal conductivity or the insulation material in [m K / W],
D_c outer diameter of the pipe casing in [m],
d_y diameter of the steel pipe in [m],
$R_{\alpha c}$ surface thermal insulance on the insulation surface in [m2 K/W].

For pre-insulated pipes the following simplifications can be made: $R_{\alpha e} = R_{\alpha c} = 0$, $D_e = D_c$ and $R_h = \dfrac{1}{4\pi\lambda_g} \ln\left[1 + \left(\dfrac{2Z}{C}\right)^2\right]$, where C is the distance between the pipes in metres.

Corresponding calculation methods are given for channel piping systems in the code.

Note: The heat transfer coefficients presented in the norm are approximations. They do not include e.g. the influence of the casing around the insulation of the DH-pipes.

4.3.2.4 *Single pipe-couple models*

Most heat loss models for pipe systems, reported in literature, deal with single pipes, (Bennonysson, A., 1991), (Dutré, W. L., 1990) and (Rahbek, J. and Svendsen, S., 1995). For district heating systems, this representation would lead to overestimation of heat loss from the piping. Hence models for heat pipe couples are proposed by (Bennonysson, A., 1991). The underlying district heating model is a rough simplification of a single source-sink system with single pipe couple model, as sketched in Figure 6, involving the following assumptions:

1. The DH system consists of a single plant (heat source).
2. The DH system consists of a single consumer (heat sink), representing all consumers and one single load.
3. A single "representative branch" represents all net branches by a single double-pipe model.

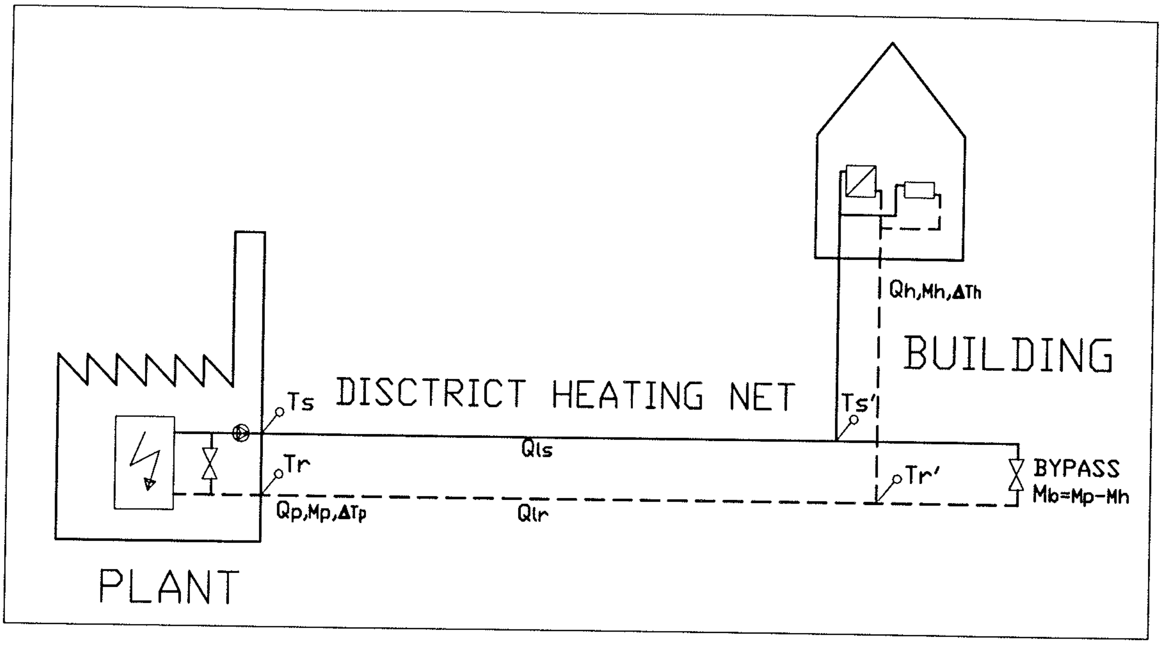


Figure 6. A simple district heating model.

In the model the assumption is made that the plant is situated on one side of the DH-piping and the (single) consumer on the other side of the net. The net is modelled by a distribution part, a connection pipe and a bypass where the forward pipe (solid line) is connected to the return pipe (dashed line). The model defines a set of temperatures relevant for heat loss calculations, T_s for the supply and T_r for the return temperature at the plant and similar temperatures T_s' for the supply and T_r' at the user. The mass flow rate at the plant, M_p, gets at the user connection point diverted into M_h through the user installation (house) and M_b through the bypass.

The basic layout of the DH system is used by the following steady-state calculations, but will also be applied in the dynamic model in Part 2.

4.3.2.5 Steady-state computations

In steady-state computations the assumption is made that the temperature and flow conditions are constant in time. The temperature along the district-heating pipe is unknown and so the heat loss of the pipe. To get an estimate for the heat loss, the temperature development along the pipe is supposed by simple temperature profiles. (Bøhm, B., 1998) proposes a linear temperature profile, as (Christensen, K. and Howald, P. B., 1987) prefer a non-linear, logarithmic temperature development along the pipes.

The linear steady-state model is taught at the course in district heating at the Technical University of Denmark, (Bøhm, B., 1998). The heat loss for the supply pipeline is found by

$$Q_{ls} = U_1\left(\overline{T}_s - T_g\right) - U_2\left(\overline{T}_r - T_g\right) \tag{8}$$

The mass flow ratio, s between the mass flow through the house installation, M_h, and the total flow in the DH, M_p, is defined by $s = \frac{M_h}{M_p}$. The ratio is then used for a simple mixing model for the mass flows through the building and the bypass, defined by

$$T_r^{'} = T_s^{'} - \Delta T_h \cdot s \tag{9}$$

where ΔT_h is the temperature difference over the building connection in K. The model leads to two equations with two unknowns, the temperature to the building $T_s^{'}$ and the return temperature at the plant T_r.

$$\begin{aligned} Q_p &= M_p \cdot c_p (T_s - T_r) = Q_h + Q_{l,tot} \\ Q_{ls} &= M_p \cdot c_p (T_s - T_s^{'}) \end{aligned} \tag{10}$$

Inserting expressions (1) and (2) to the set of equations in (10) and calculating the temperatures of the two pipelines as simple arithmetic averages, we get the final set of equations (11) that can be solved.

$$\begin{aligned} M_p \cdot c_p (T_s - T_r) &= Q_h + 2(U_1 - U_2) \cdot \left[\frac{T_s + T_s^{'} + T_r + T_r^{'}}{4} - T_g \right] \\ M_p \cdot c_p (T_s - T_s^{'}) &= \left[U_1 \left[\frac{T_s + T_s^{'}}{2} - T_g \right] - U_2 \left[\frac{T_r + T_r^{'}}{2} - T_g \right] \right] L \end{aligned} \tag{11}$$

The corresponding model, assuming non-linear temperature distribution along the district heating pipe as proposed by (Christensen, K. and Howald, P. B., 1987), leads to a set of differential equations for the supply and return pipes, respectively. The equations include the heat capacities, heat loss to the surrounding ground, heat exchange between the pipes (which is estimated to be 3% for the supply and 10% for the return pipe) and heat transfer due to friction between liquid and piping. By introducing some auxiliary quantities, the equations can be simplified leading to two coupled ordinary differential equations.

$$\begin{aligned} \frac{d}{dx}(\dot{m} \cdot c_p \cdot \theta_s) &= -U_1 \cdot \theta_s + U_2 \cdot \theta_r \\ \frac{d}{dx}(\dot{m} \cdot c_p \cdot \theta_r) &= -U_1 \cdot \theta_r + U_2 \cdot \theta_s \end{aligned} \tag{12}$$

where θ_s is the difference between ground temperature and outlet temperature of the supply pipe in K *or* °C and θ_r is the difference between ground temperature and outlet temperature of the return pipe in K *or* °C. Inserting the temperatures at the plant, T_{s0} for the supply pipe and T_{r0} for the return pipe, the set of equations can be solved for the position x along the pipe if boundary conditions are known.

$$\begin{aligned} \theta_s &= \theta_{s0} \cdot \cosh(\beta\, x) - (A \cdot \theta_{s0} - B \cdot \theta_{r0}) \cdot \sinh(\beta\, x) \\ \theta_r &= \theta_{r0} \cdot \cosh(\beta\, x) + (A \cdot \theta_{r0} - B \cdot \theta_{s0}) \cdot \sinh(\beta\, x) \end{aligned} \tag{13}$$

where the following approximations are valid for pre-insulated pipes: $A \cong 1$, $B \cong \frac{U_2}{U_1}$, $\beta \cong \frac{U_1}{\dot{m} c_p}$ in [m^{-1}]. For pre-insulated pipes we find here from the temperatures at the consumers, $x=L$,

$$\theta_{s,L} = \theta_{s,0} \cdot e^{(-\beta L)} + \theta_{r,0} \frac{U_2}{U_1} \cdot \sinh(\beta \mathrm{L})$$
$$\theta_{r,L} = \theta_{r,L} \cdot e^{(-\beta x)} + \theta_{s,L} \frac{U_2}{U_1} \cdot \sinh(\beta \mathrm{L}) \qquad (14)$$

If $\beta L \ll 1$, the second terms in (14) can be simplified to $\theta_{r,0} \frac{U_2 L}{\dot{m} c_p}$ and $\theta_{s,L} \frac{U_2 L}{\dot{m} c_p}$. The set of equations can now be solved by standard techniques. Note: The Theta-notation refers to temperature differences to the ground temperature, e.g. $\theta_{r,L} = T_r' - T_g$. Similar to the Bøhm-approach, this method leads to a couple of equations that can be solved explicitly.

→Given similar assumptions, the two calculation methods lead to the same temperatures at the consumer's and the plant. The heat loss is however more realistic for the non-linear temperature profile assumption.←

5. Precondition Modelling for Load Components

Heat loads are strongly dependent on the changing surroundings. The consumer demands are changing strongly and climatic parameters are shifting. The consumer's demands are discussed in relation to the given component models in section 4. The climatic parameters will be worked through in this section. The climatic quantities and simplification to them will be discussed to find some applicable models for these input parameters to given load models with given complexity.

One approach of simplifying meteorological data is to collect a set of measured weather data from a series of years to a single representative "year". For simulation of buildings and solar modelling under Danish weather conditions, two reference data sets are used in general, the old Test Reference Year (TRY) and the Design Reference Year (DRY). The former is described by (TRY, 1982) and the design data set by (Jensen, M. J. and Lund, H., 1995). These reference years will be discussed and compared with other data sets available, in section 5.3.

An alternative approach to the reference data sets is the simplification of individual climatic parameters to simple mathematical models. In the following a few simplified climatic models are described, followed by an evaluation of the reference year representation. As mentioned above wind speed and relative humidity are not affecting the heat loads significantly. Hence focus is put on the modelling of ambient temperature, the ground temperature for heat loss estimations and the solar irradiation only.

5.1 Simplified representation of the ambient temperature

The ambient temperature is fluctuating rapidly during the days, but behaves rather systematically during the year. Based on this observations attempts are made to simplify the data. (Werner, S. E., 1984) uses multi-regression analysis and, among others, (Bøhm, B., 1999a), (Rose, J., 1999) and (Dahm, J., 1998) apply a simple regression analysis for the determination of a representation for the yearly change in ambient temperature. A similar approach is applied in the European Norm, (CEN, 1999) for thermal heat loss modelling in buildings on monthly basis. The proposed function can be generalised to include other time periods too, leading to the following equation

$$T_a = \overline{T}_a + \widehat{T}_a \cdot \cos\left(2\pi \frac{(\tau - \tau_c)}{N}\right) \qquad (15)$$

where
T_a is the ambient temperature in [°C],
$\overline{T}_a$ mean temperature over the given period in [°C],
$\widehat{T}_a$ amplitude of the variations over the given period in [°C],
τ time in the given unit,
τ_c time for which the minimum value is obtained, same unit as time,
N number of observations corresponding to the time unit or the periodic of the cosine function.

Note: The Cosine-function can be exchanged by the Sinus-function according to the relation $\cos(x) = \sin(x + \frac{\pi}{2})$.

By analysing data from the Design Reference Year for Denmark (Jensen, M. J. and Lund, H., 1995) the following regression data fit, shown in Figure 7, can be found applying the CEN-model for the ambient temperature.

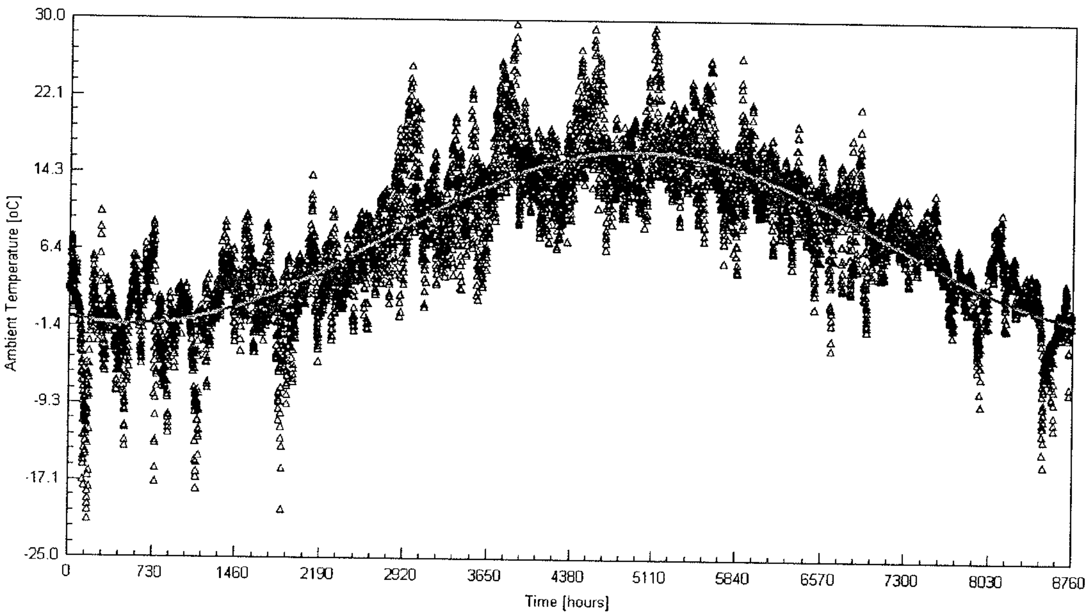


Figure 7. Result from regression analysis of ambient temperature found in DRY reference weather data set by applying the extended CEN-model of expression (15).

In Figure 7 we find both the strongly fluctuating hourly temperature pattern and the rather clear periodic behaviour of the ambient temperature during the year. The regression analysis leads to the coefficients that can be entered into formula (15). The findings are compared with coefficients from other authors in Table 4.

Table 4. Constants found in literature to insert into expression (15).

Source	$\overline{T}_a$	$\widehat{T}_a$	τ_c	N	Unit	Data
Own regression analysis[1]	7.8	8.9	562	876 0	Hour	DRY
			0.7	12	Month	TRY
(Rose, J., 1999)	8.8	8.5	1.5 [2]	12	Month	DRY
(DANVAK, 1999)	≈ 9	≈ 9				
(TRY, 1982)						TRY
Reference Year	8.1					
Measured 1959-73	7.7					
Measured 1931-60	7.9					

We find from Table 4 that the resulting coefficients found by the different authors are varying with a tendency towards low average values in TRY-representations. No final conclusion is made here, but for further modelling the coefficients found in this report are applied for simulations with the Danish DRY reference year.

5.2 Simplified representation for an undisturbed ground temperature

Most models for simulation of thermal behaviour of buildings and district heating assume the existence of an undisturbed ground temperature. This undisturbed ground temperature is in detail discussed in (Bøhm, B., 1999a). The same reference gives an overview of the theories applied for undisturbed ground temperature approximations. Based on this "virtual" ground temperature, the heat loss from such systems to the ground can be estimated. The temperature is directly coherent with the simplified ambient temperature discussed in the foregoing section.

Most approaches for defining the undisturbed ground temperature are based on the theory for semi-infinite bodies. Here a one-dimensional heat transfer problem is assumed. The ground surface defines one boundary and an assumed plane at infinite depth with uniform thermal properties defines the other boundary. By these simplifications the ground temperature, T_g, changing in time, τ, can be described by the differential equation $\frac{dT_g}{d\tau} = \alpha_g \frac{d^2T_g}{dx^2}$, where α_g is the thermal diffusivity of ground material in m²/s, and x the depth in metres. The thermal diffusivity of the ground can be obtained by $\alpha_g = \frac{\lambda_g}{\rho_g \cdot c_{p,g}}$, where λ_g is the thermal conductivity in W/m K, ρ_g and $c_{p,g}$ are the density in kg/m³ and the specific heat capacity in kJ/kg K of the ground material, respectively.

Note that the ground characteristics are not very uniform and that hereby the model must be seen as a very strong simplification. However, constant values for the ground materials are mostly applied. (Christensen, K. and Howald, P. B., 1987) suggest $\alpha_g \approx 0.7 \cdot 10^{-6}$ m²/s for typical Danish ground conditions. More detailed values can be found in (Porsvig, M., 1986) for the main materials found in Danish ground.

[1] Regression analysis results: Coefficient of multiple determination $R^2 = 0.73$.

[2] Calculated by sin-formula with value $\tau_c = 4.5$ which is in cosine-formula $\tau_c = 1.5$.

Solutions to the differential equation above are manifold. (Christensen, K. and Howald, P. B., 1987) use a Fourier-analysis, including the first six series, and find the following constants describing the ground temperature oscillation during the year at given depths.

Table 5. Constants applied by (Christensen, K. and Howald, P. B., 1987) to determine the ground temperature as monthly values, inserted into expression (16).

n	1	2	3	4	5	6
C_n	10.189	1.718	0.124	0.388	0.459	0.123
δ_n	3.551	0.383	2.805	0.110	4.541	0.864

$$T_g = 8.788 + \sum_{n=1}^{6}\left[C_n \cdot e^{-\varpi_n \cdot x} \cdot \cos\left(2\pi\, n\frac{\tau}{N_{year}} - \omega_n \cdot x\right) - \delta_n\right] \tag{16}$$

where $\omega_n = \sqrt{\dfrac{n \cdot \pi}{\alpha_g N_{year}}}$ and N_{year} is the number of seconds in a year. The ground temperature found by this algorithm is shown in Figure 8.

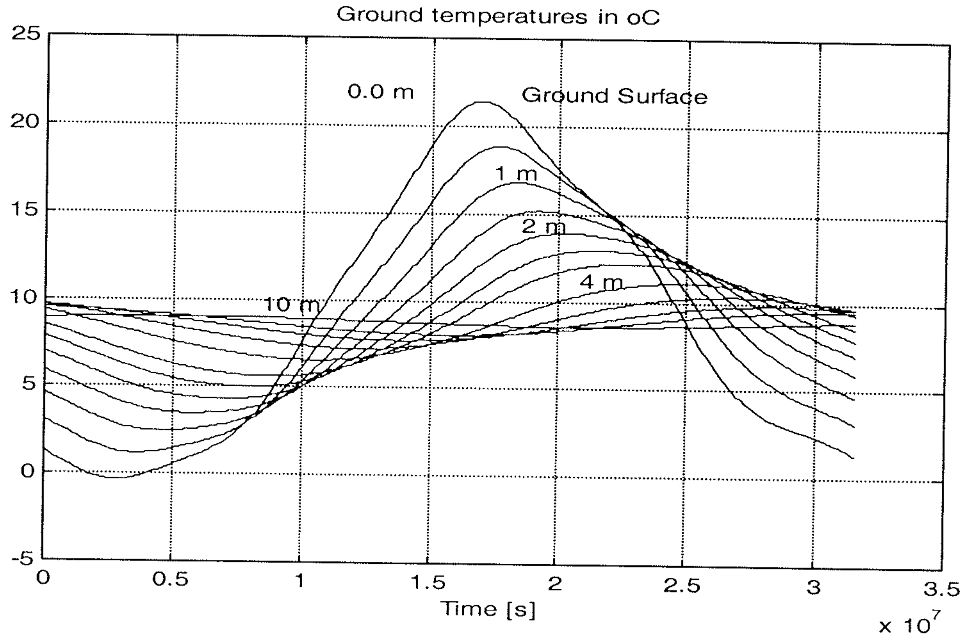


Figure 8. Ground temperature in different depths, x, computed by expression (16) and Table 5.

Figure 8 gives an idea of the damping of the ground temperature with depth. We see that the amplitude of the oscillating ground temperature is decreasing. At a depth of approximately 10 metresthe temperature gets close to steady.

A more general approach for finding solutions to such one-dimensional, transient heat transport problems can be found by so-called error-function solutions described e.g. in (Claesson, J. and Hagentorft, C-E., 1994). (Dahm, J., 1998) applies the error function method and derives the following expression for the undisturbed ground temperature, $T_{g,x}$ in°C, at depth, x, in metres, where daily fluctuations are neglected.

$$T_{g,x} = \overline{T}_g - \hat{T}_g \cdot \exp\left(-2\pi\frac{x}{\kappa}\right)\cdot\cos\left(2\pi\left[\frac{\tau_c}{N}-\frac{x}{\kappa}\right]\right) \qquad (17)$$

where τ, is the time , N, the total number of time-steps for the simulation interval, p, that must correspond to the time-step chosen, τ_c, is the time where the coldest temperature of the year occurs. κ is by mistake defined as $\kappa = 2\sqrt{\pi \cdot \alpha_g \cdot N}$ but must be corrected to $\kappa = \frac{2}{\sqrt{\pi \cdot \alpha_g \cdot N}}$.

Comparing the two models for the most relevant depth for building and DH-pipe heat loss simulations, we find the following temperature profiles.

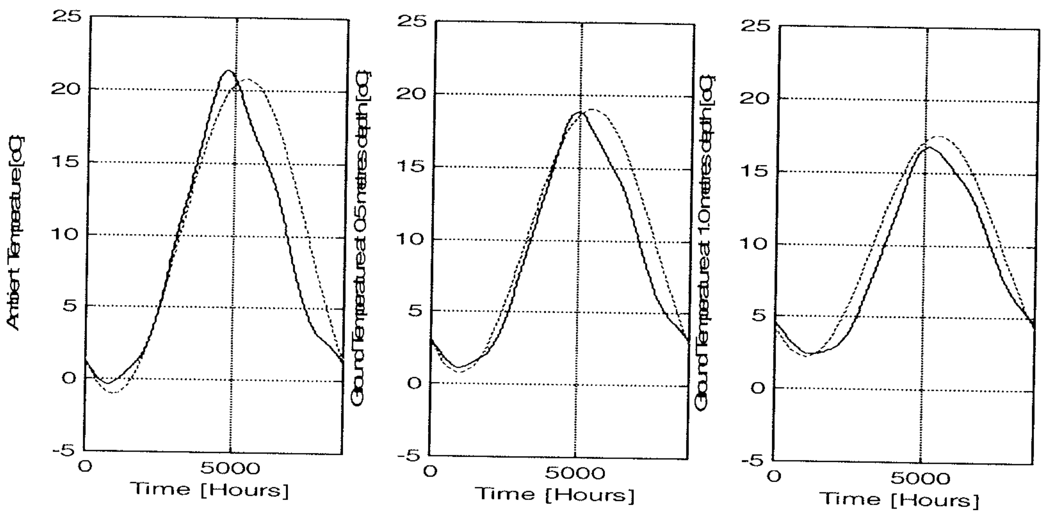


Figure 9. Surface and ground temperature in different depth, computed by expression (16) (solid line) and (17) (dashed line). Yearly temperature profile at ground (left), at 0.5 metre depth from surface (middle) and at 1 metre below the surface.

We see clearly from Figure 9 that in general the Dahm-approach computes higher temperatures at the presented depth. The Dahm-model considers the yearly oscillation only as the Christensen-Howald model considers other periodical systematic changes, too. Due to the fact that the uncertainties for the ground characteristics are dominating, the difference between the methods is minimal and therefore it is recommended to apply the simpler algorithm by Dahm.

5.3 Simplified representation for cold water supply temperature

Modelling of hot-water supply demands on assumptions on the cold water to be warmed up. Mostly one assumes a constant average temperature during the years. According to (Werner, S. E., 1984), (Aronsson, S., 1996) and (Yang, L., 1994) the cold water can be represented by a smooth sinus curve. The resulting equation applied in the IEA SHC Task 26 work, (IEA SHC Task 26, 1999), is described by

$$T_{cw} = \overline{T}_{cw} - \hat{T}_{cw}\sin\left(360\left[\frac{\tau + 24\cdot(91.25+\tau_s)}{8760}\right]\right) \qquad (18)$$

where T_{cw} is the cold water supply temperature in [°C],
$\overline{T}_a$ mean cold water temperature over the given period (year) in [°C],
$\hat{T}_a$ amplitude of the variations over the given period in [°C],

τ time in the given unit,

τ_s time for which the maximum value is obtained, same unit as time,

Note: The values involved in equation (17) are based on the chosen hourly time intervals. For other time intervals these values must be adjusted. A more general formulation can be derived from equation (15).

(Schultz J.M., 1991) measured the yearly shift of cold water temperature. From these results the resulting coefficients to be inserted to the sinus-formed curve can be extracted, see Table 6.

Table 6 Coefficients for sinus model of cold water under Danish conditions in °C.

Source	Yearly average	Amplitude	Min	Max
Extracted from (Schultz J.M., 1991)	8.75	6.25	March 2	Aug. 15
(Carlsson, P. F., 1995)			Dec. 10	July 14

As we see from Table 6 there is a large deviation of cold water measurements and hereby the uncertainty is rather large. →In the following model work the own findings for the ambient temperature fluctuation and the cold water values by Schultz will be applied.←

5.4 Comparison between Danish reference year data

In this section the most obvious weather data sets are compared. There are two official data sets, the older Test Reference Year (TRY) and the later Design Reference Year (DRY). The former is described in (TRY, 1982) and the design data set by (Jensen, M. J. and Lund, H., 1995). The main difference between the Danish TRY and DRY data sets is the way data is gathered to a representative data set. TRY is a summary of real measured hourly data in series of one month based on data collected between 1959-1973. DRY is designed to reflect some characteristics of the weather by a summary of hourly and 5-minute data measurements from 1975-1990. The data is prepared to fit the monthly mean values for the period. To design these characteristics the data was composed systematically from a collection of 15 years' measured data.

European TRY data sets can be found in (TRY, 1985) and global sets can be generated by the computer program METEONORM by (Remund, J., Lang, R., and Kunz, S., 1997). The simulation program applied in this work, TRNSYS (Klein, S. A. and many others, 1996), is distributed with two data sets for Danish climatic conditions, the **copen.try** and the **copennew.try**.

The objective of this section is to compare and discuss the mentioned data sets and hereby to give the reader an idea which set to apply for certain computations. All data sets, applied by the Department of Buildings and Energy, are available at the World Wide Web: http://www.ibe.dtu.dk/forsknin/cshp/meteo/meteo.htm.

The author does not know the origin of some of the sets. Therefore the TRY data sets are compared and discussed by comparison with the "original" data set from SBI, (SBI, 1982). Hereafter the SBI-TRY set is compared with the DRY data set to give some ideas of the differences and hereby some estimates of the expectable performance for central heating systems.

5.4.1 TRY representations

As mentioned above, numerous meteorological data sets are distributed in literature, especially computer programs are distributed with some kind of data sets. Here an overview of the files distributed with relevant programs applied in simulation of energy systems is given.

Note that the remarks on the "Origin" is based on an analysis of the data, a monthly value comparison, a correlation analysis of hourly data for ambient temperature and solar irradiation components.

→It is advisable not to use data sets with unknown origin or data sets diverging from the originals even though the differences may seem small.←

Filename	**Cph_try.dat**
Application	TSBI3
Reference	Computer simulation program for building simulation by the Danish Building Research Institute, (Johnsen, K., Grau, K., and Christensen, J. E., 1993).
Origin	Original data set by SBI.

Filename	**REFAAR.INP**
Application	Kappesol, Spiralsol
Reference	Simulation programs for solar applications, developed at the Dept. of Buildings and Energy, Technical University of Denmark.
Origin	Original by SBI.
Comments	Not compared due to rather complex data structure.

Filename	**TRY_COP**
Application	Various applications by the author and others at the Dept. of Buildings and Energy, Technical University of Denmark.
Reference	
Origin	Original by SBI.
Comments	Fully identity with original data supplied by SBI, (SBI, 1982).

Filename	**Copennew.try**
Application	TRNSYS
Reference	(Klein, S. A. and many others, 1996)
Origin	Unknown
Comments	Comparison of hourly data by correlation matrix plot shows Recommendation: Do apply only if no other data set is available.

Filename	**Copen.try**
Application	TRNSYS
Reference	(Klein, S. A. and many others, 1996)
Origin	Unknown
Comments	Recommendation: Do apply only if no other data set is available.

The computer program Meteonorm is able to generate weather data sets for many sites in the world. The program would be relevant for general modelling. Hence the data set from the program for "Copenhagen -Taastrup" is compared with the original data set.

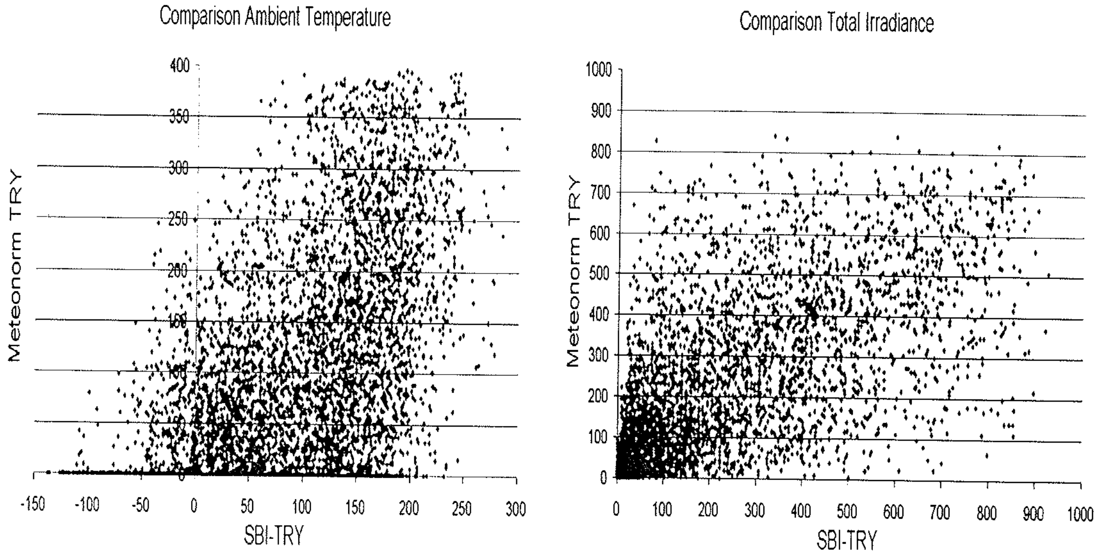


Figure 10 Correlation plot for TRY data from the SBI-data set and the Meteonorm generated data set.

It is rather clear from Figure 10 that there is a week correlation on hourly data between the two data sets for the ambient temperature and the total solar irradiance. Especially for the ambient temperature, a systematic deviation is observed. Hence the data is not really a TRY-representation. Comparing monthly values we find the results as presented in Figure 11.

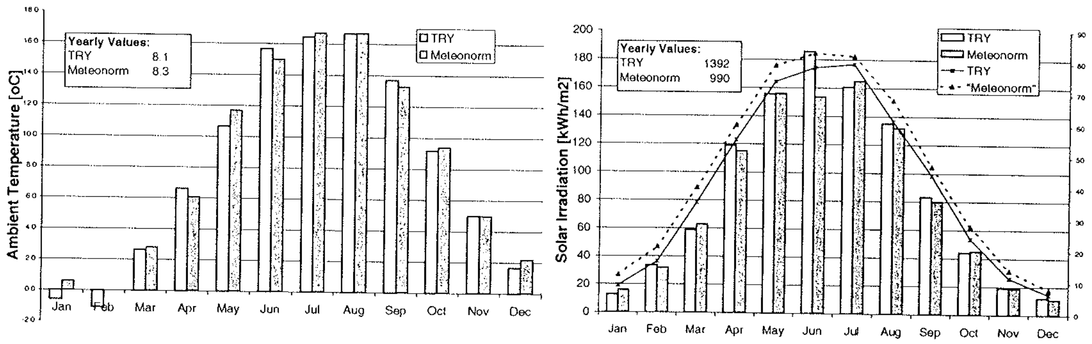


Figure 11 Comparison of monthly data from the original SBI TRY data set and the Meteonorm generated data set.

The findings based on hourly data are confirmed by the findings based on monthly data analysis in Figure 11. The two data sets are not identical, even though some similar patterns can be found.

→If using a TRY-data set, the original **CPH_TRY** data set files from SBI should be applied only, downloadable at http://www.ibe.dtu.dk/forsknin/cshp/meteo/meteo.htm.←

5.4.2 DRY representations

DRY representations handled in this work are all prepared directly on the original data. Hence no comparison must be made. Here the relevant representations.

Filename	**DRYORIG.COP**
Application	
Reference	(Jensen, M. J. and Lund, H., 1995)
Origin	**The original data set!**

Filename	**DRY12_h.cop** and **DRY12_5m.cop**
Application	SOLSIM
Reference	(Rahbek, J. and Svendsen, S., 1995)
Origin	Original
Comments	The data sets are not complete, including ambient temperature, solar irradiation measurements, wind speed and relative humidity data only.

Filename	**DRY_h.cop**
Application	
Reference	by the current author as a part of this thesis.
Origin	Original.
Comments	Original except 5-minute values. Prepared by a Perl-script to be found on the Internet.

→If using a DRY-data set, the original DRY_h.cop data set files from DTU should be applied only, downloadable at http://www.ibe.dtu.dk/forsknin/chps/meteo/meteo.htm.←

5.4.3 TRY contra DRY

In the above section the different meteorological data sets are compared to find the "original" data sets. In this section the original TRY data set, **CPH_TRY** is compared with the data set by Jens Rahbæk, Dept. of Buildings and Energy, DTU (Filename: **Dry12_t.cop** and **Dry12_5m.cop** for hourly and 5-minute values, respectively): 1) to be able to chose between TRY and DRY for a given purpose. 2) to be able to estimate the impact of the choice on the expected results of computations.

5.4.3.1 *Ambient Temperature in DRY and TRY*

Average monthly values for the DRY and the TRY reference data sets are plotted in Figure 12 for the ambient bulb air temperature. In the left plot, extreme values for hourly and monthly observations are plotted together with the monthly average values. In the right plot, the same data is compared with DRY and TRY average data.

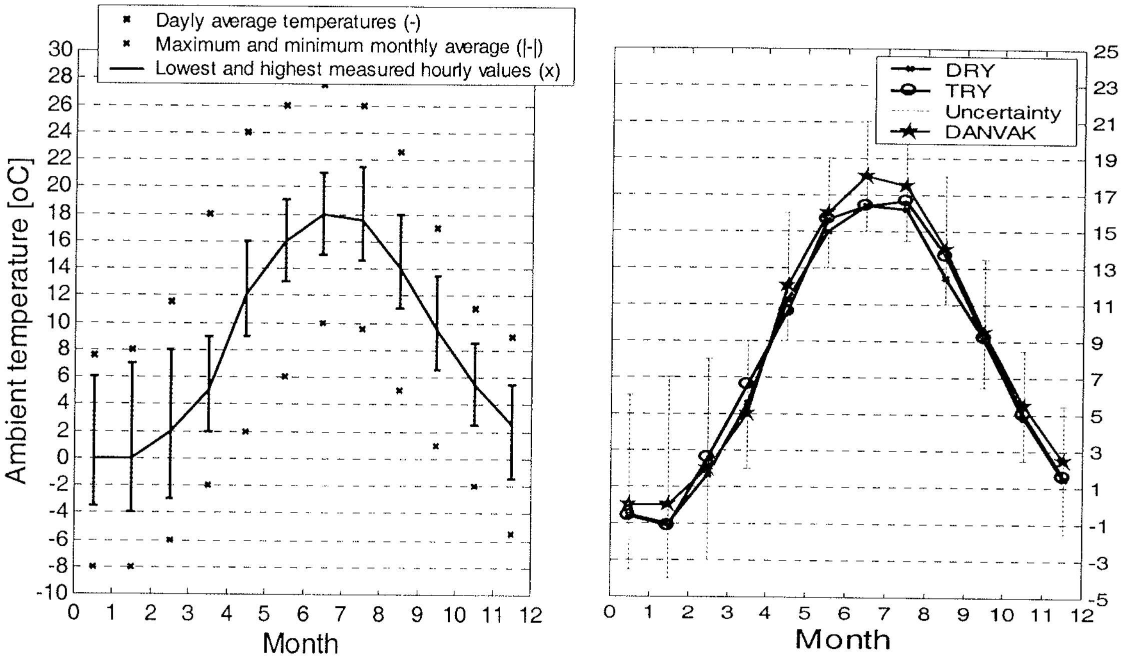


Figure 12. Ambient air temperatures: Left: Statistical representation of measured data from 1931-1960. Source (DANVAK, 1999). Right: Comparison of average monthly values for DRY, TRY and DANVAK measurements. Note the different scale for the ordinate axis.

We see from Figure 12 (left) that the average monthly ambient temperature is varying as a periodic curve during the year. We also see that the hourly average values show much more extreme values than the monthly observations. More findings can be extracted from of the figure, which is up to the reader.

In the right plot of Figure 12, the DRY and TRY monthly average values are plotted to the DANVAK observations. Focusing on monthly average values we find that all three data sets are tight. We also find that the reference data sets seem to have the same amplitude but a lower yearly average than the DANVAK-data. Seen form this point of view the two reference data sets seem to be representative for a very long range of measured data. On the other hand, this is not surprising, noticing the very large variety in weather pattern, represented by the DANVAK-data.

Having concluded that both the DRY and the TRY data sets are representative for Danish weather conditions, the data will be compared by a closer comparison in the following.

The monthly average values for the two data sets are presented in Table 7.

Table 7. Monthly and yearly average values for ambient temperatures found in the reference-data sets, DRY and TRY. Figure (right): Difference (DRY-TRY) for monthly and yearly deviation of ambient temperature.

	Ambient temperature °C		
	DRY	**TRY**	**Difference**
January	-0.5	-0.6	0.1
February	-1.0	-1.1	0.1
March	1.7	2.6	-0.9
April	5.6	6.6	-1
May	11.3	10.6	0.7
June	15.0	15.7	-0.7
July	16.4	16.4	0
August	16.2	16.7	-0.5
September	12.5	13.7	-1.2
October	9.1	9.2	-0.1
November	4.8	5.0	-0.2
December	1.5	1.6	-0.1
Year total	**7.8**	**8.1**	**-0.3**

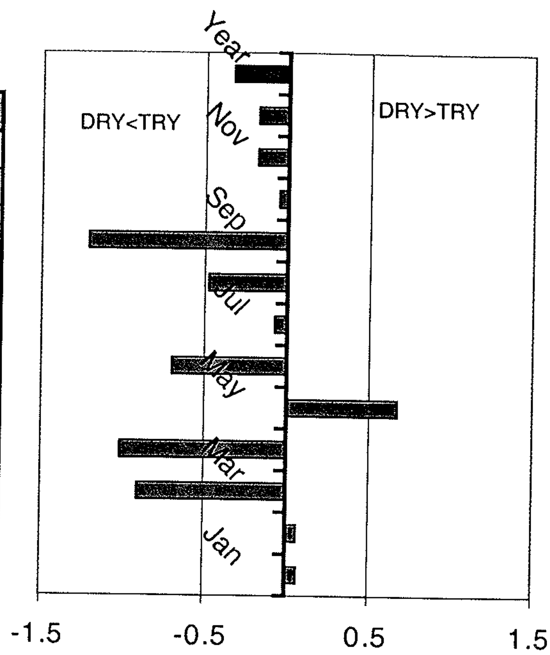


Figure 13. Difference in ambient air temperatures for the DRY and the TRY weather data sets. Note: For positive values the DRY value is larger than the TRY value.

From Table 7 we find that the monthly and yearly average values for the ambient temperatures are not diverging very much between the two data sets. However, the plot in Figure 13 to the right clearly shows a tendency of having a colder average temperature for the TRY data set. →From this point of view, one will expect that the heat load estimated by the TRY data set leads to a higher total load compared to the DRY data set.←

5.4.3.2 Solar Irradiation in DRY and TRY

Monthly and annual average values for the Danish DRY and the TRY data sets are compared in Table 7.

Table 8. Monthly and yearly average values for the total and diffuse solar irradiation on a horizontal plane in kWh/m² from the reference-data sets, DRY and TRY.

Month	Total solar irradiation kWh/m²			Diffuse part of solar irradiation kWh/m²		
	DRY	TRY	Difference in %	DRY	TRY	Difference in %
January	15.5	12.6	18.7	10.2	8.6	15.7
February	32.0	33.3	-4.1	19.6	16.3	16.8
March	65.0	58.7	9.7	36.5	35.2	3.6
April	114.0	118.8	-4.2	57.0	55.3	3.0
May	163.4	155.5	4.8	73.2	73.9	-1.0
June	164.9	185.6	-12.6	82.7	78.4	5.2
July	160.0	160.8	-0.5	82.1	79.5	3.2
August	134.0	134.9	-0.7	64.3	61.4	4.5
September	81.7	83.2	-1.8	43.0	44.3	-3.0
October	42.6	43.9	-3.1	23.1	24.2	-4.8
November	18.9	19.2	-1.6	11.6	11.6	0.0
December	10.3	11.9	-15.5	7.3	6.5	11.0
Year total	**1002.0**	**1018.0**	**-1.6**	**510.5**	**495.2**	**3.0**

The values of Table 8 are reflected in the figures below.

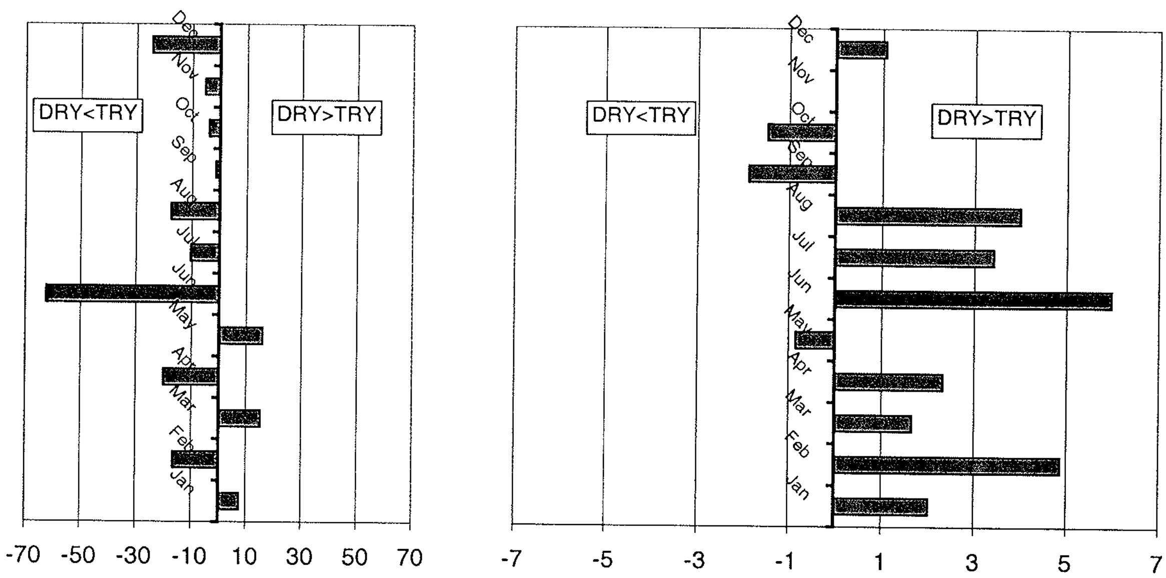


Figure 14 Difference plots for Solar Irradiation Components. Left: Direct Part (Beam radiation). Right: Diffuse part. Positive values: DRY is larger than TRY-values.

From Table 8 and Figure 14 we find that:

- there is no significant differences in the yearly average values for the solar irradiation of the DRY and the TRY weather data sets.

- the yearly value is not reflecting the large discrepancies in monthly average values.
- both the direct and the diffuse parts of the solar radiation are systematically different. The direct part is predominantly larger for the TRY and the diffuse part is larger for the DRY.
- The direct solar irradiance for June shows much larger differences than the other months. Due to the fact that the summer months are most relevant for heating and solar heating, the large difference in June is assumed to lead to severe differences for simulations with the two data sets.

→From this observations we can conclude that the TRY data set will lead to stronger impact of solar irradiation than the DRY data set. Especially June, one of the most important months for such computations, the TRY data will lead to higher results than found with the DRY data. Due to the fact that the impact of solar irradiation on the total heat load is 1/10 of the impact from the ambient temperature, the difference will be relatively small. This is not the case for building simulation and solar technology simulations.←

Comparing the hourly data between the data sets we get the correlation plots as shown in Figure 15.

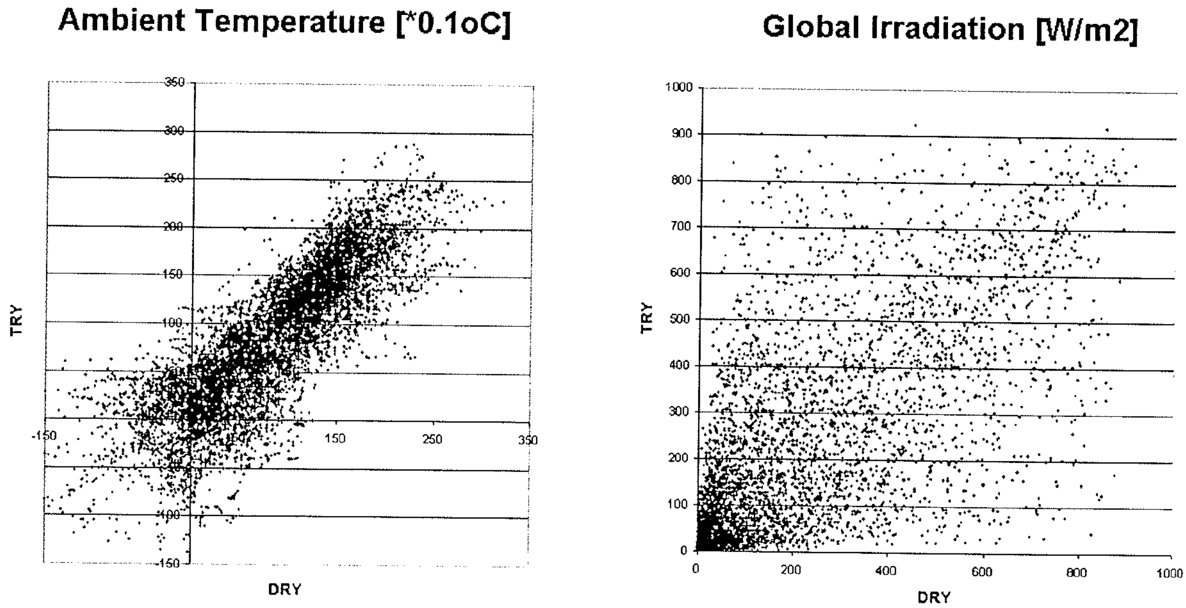


Figure 15 Comparison of hourly values for ambient temperature (left) and solar irradiance (right) for the DRY and the TRY reference year data.

From Figure 15 we find that the TRY and the DRY reference year data are

- strongly correlated for the ambient temperature.
- very weakly correlated for the solar irradiance but with no systematic deviation.

→We can conclude that the data sets are not similar and that solar irradiations are rather differently represented in the data sets.←

5.4.4 Conclusions and recommendations on reference year data

We find from this very simple investigation above

- that the two data sets are representative for Danish weather conditions.
- that the TRY and DRY reference years are not similar.
- that the yearly average values are comparable.
- that monthly average values for ambient temperature and solar irradiance differ.
- that the deviation of solar irradiance in June is rather decisive.
- that present intervals for which values are sampled, is decisive for the comparison between weather data sets.
- One should not apply reference data from unknown sources.

To give a final summary we find the following key-descriptions for the TRY and DRY, to be found on the Internet at: http://www.ibe.dtu.dk/forsknin/cshp/meteo/meteo.htm.

Table 9 Summary values for Copenhagen TRY and DRY.

Weather data	***Ib***	***Id***	***Ta***	***Hour u. 12oC***	***Degree Hours***
	[kWh/m^{2}a]	[kWh/m^{2}a]	[°C]	Sep.-Mar.	
Copenhagen (TRY)	1363	698	7.7	5944	80809
Copenhagen (DRY)	1487	676	8	5833	83706

Summary data are also plotted in Figure 16.

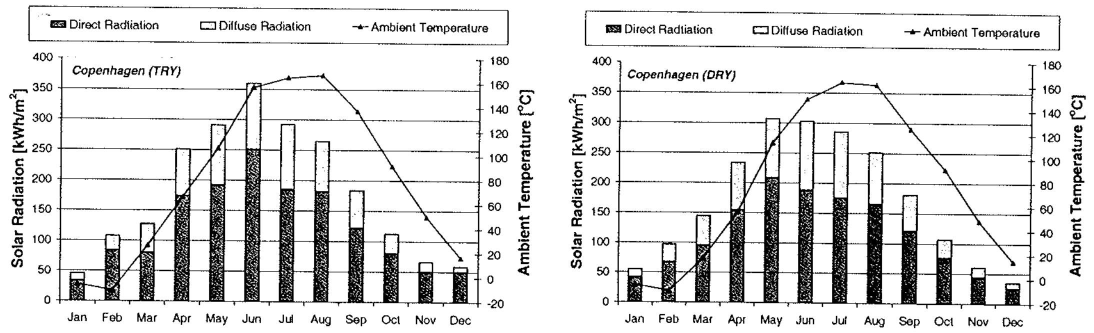


Figure 16 Summary data for Copenhagen TRY and DRY.

PART 2 - DYNAMIC HEAT DEMAND MODELLING

In PART 1, the theoretical and methodological background for load modelling is presented to give a general applicable basis. In the current part these general descriptions are used as an inspiration for the implementation in a dynamic simulation model. Hereby the generality is lost due to choice of models, parameters and modelling tool. The resulting load generation model for central heating systems will be applied in following research activities by the author and can be seen as a source for inspiration by others.

The simulation model presented her will be a numerical model where a computer interpretation is applied to represent the system behaviour to be investigated. Such an approach is widely applied in research and engineering. Examples in the application of dynamic models can be found in e.g. (Yang, L., 1994) and (Qin, L., 1998), where the models are implemented in native programming languages, in (Pálsson, H., 1997) where a rather advanced simulation environment MATLAB® is utilised and in (Dahm, J., 1999) where the simulation environment, TRNSYS®, is used for simulations of small district heating.

Before going to the individual load component models and the overall load model, gathering these component models, some few reflections are made on the methodological aspects in section 6 and on numerical subjects in section 7.

6. METHOD

The overall terms used for the here-applied method are "Modelling" and "Simulation". Modelling is the task of describing a representative model of a given object. "Simulation" is the task of using the numerical model for estimation of object behaviour. The method is popular due to flexibility, generality and due to the fact that the method is very cheap compared to many experimental alternatives.

6.1 Mathematical-physical model description

Object models that can be transformed into numerical models are described in mathematical terms. The mathematical theory of origin can be deterministic or stochastic (statistic). In deterministic theories, physical regularities are described in rules and laws, e.g. the law of energy conservation. In stochastic theory the focus is put on objects that behave apparently casual, but show some kind of statistical regularities. Both approaches have their strength. Stochastic models are superior for description of casual behaviour, such as the estimation of the time where a person is taking a bath. The drawback of such models is the difficulty for the researcher to find a source of a given respond/result. Here the deterministic models are easier to interpret by the researcher. As we will see in the following, the majority of implemented models are based on deterministic theories, but a few stochastic models are also included to cover "irregular" heat loads founded in people's behaviour.

Mathematical models typically lead to a set of equations to be solved. Dependent on the type of equations, different numerical methods are to be used. For central heating systems, the governing equations are ordinary and partial differential equations, where the latter in the most cases are simplified to a set of ordinary differential equations. The resulting set of equations is solved by "dynamic simulation".

6.2 Numerical Model Implementation

The mathematical terms, describing the real world object or a part of it is then transformed into a numerical model. For this purpose one can choose between a number of tools, spreading from very general applicable and native computer languages (C++, Fortran), over still very general but aim oriented simulation languages as (Dymola and Modelica) to graphical modelling tools (PRESIM, IsiiBat). The later are graphical interfaces for the modelling in the simulation environment TRNSYS.

6.3 Model Validation

The resulting implemented model can now be applied for input-output experiments, called simulations. However, before doing such experiments, the model must be tested to prove its realistic estimation. This task is called validation and can be performed in many ways, e.g. validation can consist of two steps:

1) Calibration: Some real world measurements are applied as inputs to the numerical model and some others are used for comparison of the simulation results. The objective of this task is to find model parameter values that give the most realistic results. In some cases results from experimental work are applied for the determination of parameter values. Also statistical methods are often applied for parameter estimation if deterministic estimations are missing.

2) Validation: The object model is applied with a minimal set of measured input data and the results are compared with real world data. The objective of this step is to demonstrate that the model, using the parameters of the first step, is producing realistic results. If this is the case the model is assumed to prepare realistic results, also for data that are not covered by the test/validation cases.

6.4 Simulation

After this two step validation we assume that the model is producing realistic results. The model is now applied for simulations. The objective of such simulations is to investigate system behaviour under unknown conditions. As an example one can change a given parameter and analyse the outputs. From such an analysis the research object can be redesigned to give the estimated responses in real world.

The method is widely applied in science and engineering. However, one has to be aware of some weakness of the method, among other:

- Often the task of describing the research object in mathematical-physical terms is based on lumping fragments from different theories. Due to the fact that the theories are based on experiments with certain limitations, this approach can lead to application of theories outside their domain.
- The model often involves a number of parameters that can be adjusted for different individuals of a given object. Cases occur where the parameters are unknown. In other cases, the methodology leads to unrealistic parameters that may be kept in the model to find realistic results.

- Validation is made in a range where knowledge of the research object is very great. The simulations are in ranges where knowledge is missing (extrapolation). The method gives no confidence in the reality of the results.
- The method results, typically, in a huge amount of (numerical) data. The interpretation of this data is a very complex task and often demands a lot of experiences by the interpreter. This subject is nearly un-discussed in literature and education and should be focussed on in the future.

7. General Numerical Considerations

In this section some general subjects of numerical simulation are discussed. First the time-dependency of a system is discussed shortly in section 7.1. The question is what to do if different characteristics involve very different time-dependencies. In section 7.2 some considerations are made on modelling and simulation of flows in pipes, the so-called advection-diffusion problem.

7.1 Dynamics

A rather detailed survey of the dynamic heat loss modelling and simulation is presented by (Bennonysson, A., 1991). Bennonysson categorises dynamic heat loss into fully dynamic and pseudo-dynamic models. For fully dynamic methods the energy and momentum equations are solved simultaneously. As, according to Bennonysson, the dynamics in pressure is approx. 1000 faster than the thermal changes, the two physical "modes" can be de-coupled and solved separately. One way to do this is by pseudo-dynamic modelling, where pressure and flows are kept at fixed values to determine the temperatures in the DH-system. Discretizing the time into appropriate short time-steps, such assumptions are realistic and hence applied in most implementations.

In the current work, pseudo-dynamic modelling is applied only.

7.2 Flow modelling – A challenge

Modelling central heating systems involves flow modelling through pipes. This particular subject causes numerical difficulties that will be discussed in this section. From this discussion the reader should be able to choose a reasonable pipe flow model for a given application. The methodology applied hereby is to go back to the root-problem, the description in form of differential equations, and to analyse the solution domain from a numerical point of view. The goal is to find a numerical method that does not bring along any numerical artefacts. The presentation is built up in the way that the problem is described in general mathematical and numerical terms.

7.2.1 Problem description

The following physical phenomenon of <u>one-directional fluid flow in pipes/cavities with symmetrical thermal surroundings</u> involves two main cases, the simple case with <u>constant flow</u> and a more complex case with <u>variable flow</u>. These flow patterns must be addressed by numerical methods. The current presentation is strongly inspired by (Barker, V. A., 1998).

Models for thermal and fluid dynamic system basically originate in formulations of energy and mass flow conservation for the given control volume, the system and its surroundings. In our case the system (control volume) is the pipe and the surroundings are the ambient temperature and the inlet flow conditions (inlet temperature and flow velocity).

The heat and mass balances for the system involve the following components:

- Fluid transport into and out of the pipe.
- Heat accumulation in the pipe and the fluid.
- Heat conduction to the surroundings.

There are a number of physical phenomena that are excluded in the current case for simplification:

- Assumption of incompressible flow.
- Assumption of one-dimensional flow in the pipe.
- Assumption of absence of friction in the system.
- Assumption of fully developed and idealised flow.
- Assumption of a flow pattern, where laminar or turbulent is explicitly defined as constant by model parameters.
- Assumption of no axial heat transports in the pipe material or the surroundings.
- Assumption of space independent ambient temperature. The ambient temperature can change in time.

In the given pipe system, the thermal and fluid dynamic phenomena are in reality coupled. The flow and fluid displacement, is driven by pressure differences along the pipe and any dynamic changes in the flow. The reaction to such changes is transferred very fast, in seconds, whereas changes in temperatures are driven by temperature differences along the pipe which are, according to (Bennonysson, A., 1991), approximately 1000 times slower. Therefore the assumption is made that the two phenomena are independent in relation to time. Such models are a subset of dynamic fluid models, called quasi-dynamic.

The physical model consists of a pipe and a fluid flowing in a given direction and heat loss perpendicular to the pipe and flow direction. No insulation or protection layer of pipe or surface is included in the current case study.

Fluid transport is part of a problem class called "advection". Heat transfer through the pipe to the surroundings can be classified as "diffusion". These classifications will play a major role in the search of numerical methods.

Before formulating these problems mathematically, the notation applied must be put into context. There are two notations common for the description of differential equations, the more formal notation $\frac{\partial u}{\partial t}$ and the simpler, u_t. The term u is a function describing the dependent parameter in time and space. In the following the simple notation is applied.

The advection problem may in general be described by a hyperbolic second-order differential equation, or in some cases by a hyperbolic first-order differential equation, written as

$$u_t = ku_x \tag{19}$$

where u is the dependent variable (in the pipe-case; the temperature),
t time,
x position in space,

k advection parameter describing the flow characteristics.

Correspondingly, diffusion can be described by a parabolic second order differential equation. Assuming a one-dimensional diffusion problem, the problem can be simplified to a first order differential equation, as

$$u_t = \alpha u \qquad (20)$$

where α thermal diffusivity for the pipe material in m^2/s, describing the thermal properties of the pipe material.

1) Concentrating on a pipe of given length, L, as the control volume, 2) introducing the conditions of the pipe surroundings as u_o and 3) applying a heat and mass balance to the system, the two differential equations can be connected to the final differential equation

$$\boxed{u_t = -ku_x - \alpha(u - u_0) \qquad (21)}$$

where the sign of the constant, k, describes the flow direction.

The problem, as any differential problem, can be visualised as sketched in Figure 17.

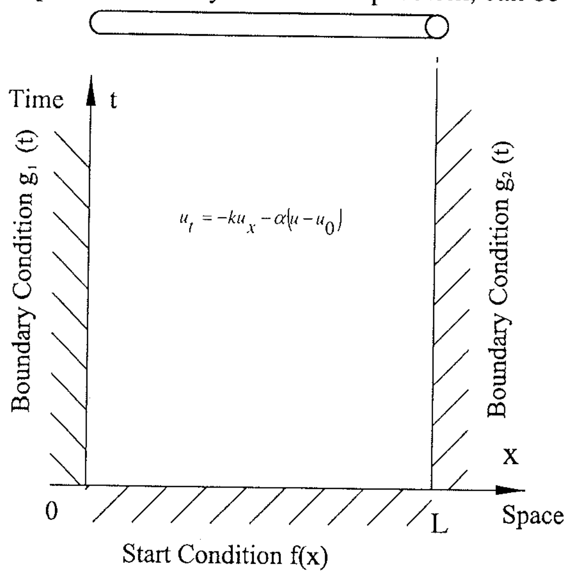


Figure 17. Visualisation of the space and time domains of the pipe problem. The problem domain is bounded on three sides; at the bottom by the initial condition, and to the left and right by boundary conditions at the inlet and the outlet.

The initial (start) condition describes the values for the dependent variable, u, along the space domain, x, at the beginning of the computations, $t=0$. The boundary conditions describe the development of the boundaries in time. More about these conditions later. Relevant for the understanding of the current case is to know that the space domain describes the pipe length limited to the length, L. No limit is defined in time.

Numerical methods for solving the problem (21) are discussed in (Barker, V. A., 1998). In general partial differential equations are numerically solved by discretizing the problem. There are two overall techniques for discretizing the problem, Finite Element Methods (FEM) and Finite Difference Methods (FDM). Due to its simplicity the latter is applied in most cases and will be discussed in this work.

Replacing the differential terms of equation (21) by different approximations leads to a difference formulation of the problem. Solving this equation for carefully chosen time and space intervals, leads to a realistic, approximate solution for the exact differential equation. The error can be estimated as shown later in this text.

Applying difference approximations, the space and time domains are discretized into finite intervals, steps, saying, "to impose a grid on the domain". In most cases the grid is regular in both directions (space and time) as shown in Figure 18.

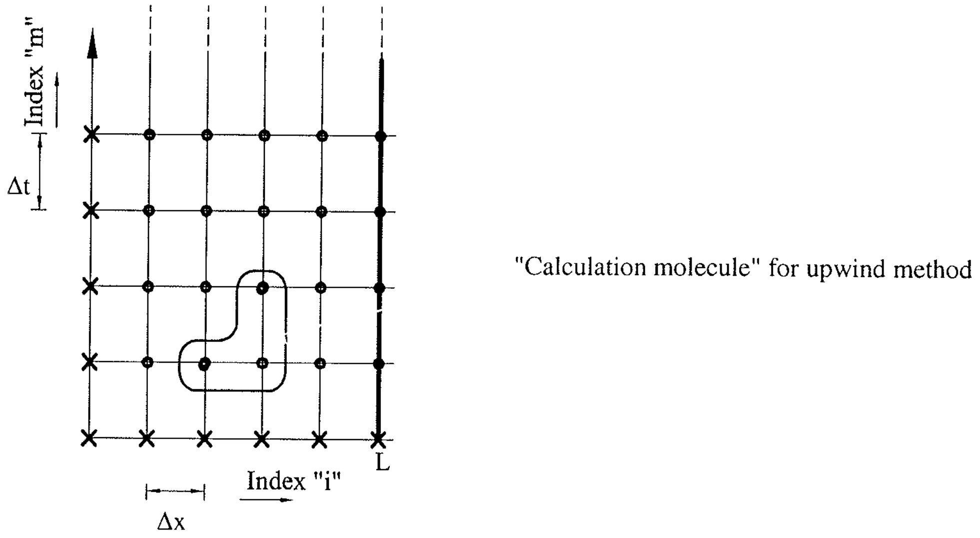


Figure 18. Visualisation of grid imposed on the problem domain. In the space domain, the grid with index, i, and a step length of Δx, and in the time domain with index, m and a step length Δt. The cross-signs describe the known values at the boundaries. The circles represent the discrete points to be calculated values. The calculation molecule will be discussed later in this text.

The method is now to calculate the unknown internal cross-points between time and space-steps (for each circle).

As indicated in Figure 17, the problem domain is bound on three sides, at the bottom by the initial conditions and to the right and left by boundary conditions. In our case the boundary condition to the right ($x=L$), the outlet temperature, is not known and is part of the values to be determined by the numerical solution. The general form for such problems in the pure initial value problem form can in the currently applied notation be formulated as:

$$\begin{aligned} &u_t = -\Phi_1\,(x,t,u)\,u_x + \Phi_2(x,t,u), \qquad -\infty < x < \infty, t \geq 0 \\ &u(x,0) = f(x), \quad -\infty < x < \infty \quad \text{and} \quad u(0,t) = g(t) \end{aligned} \tag{22}$$

where Φ is the function of one or more variables. In our problem we find $\Phi_1(x,t,u) = k$ and $\Phi_2(x,t,u) = \alpha(u - u_0)$. The function $f(x)$ describes the initial conditions and $g(t)$ the boundary conditions at the inlet, the inlet temperature and flow velocity. These conditions depend on the given computation.

The general methods, unfortunately, are not capable of solving the flow problem due to the fact that the outlet temperature in the above formulation is a boundary condition to be known for any time step. This is not the case for the pipe problem where the outlet temperature is one of the main results to be found. To escape the missing boundary problem, one could apply one of the following assumptions:

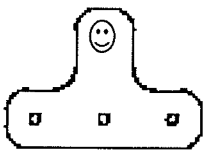
1. The dependent variable, u, is constant or known. This is not realistic.
2. The derivative of the dependent variable in time is zero or known. This would influence the solution, which is not acceptable.
3. The derivative of the dependent variable in space is zero or known. This tells us that there is no heat loss at the end of a pipe. This is no fatal mistake, but does not seem realistic.
4. The derivative can be found as a smooth function of the derivative accessible along the pipe (e.g. found as differential of the temperatures).

All the given proposals are more or less wrong or inadequate. The goal is to find a numerical method that is able to solve the differential equations without knowing the second boundary condition. Before doing so, some most important numerical techniques for the solution of first-order hyperbolic problems will be presented and discussed inspired mainly by (Barker, V. A., 1998) and (Pálsson, H., 1997).

Many methods have been found for the difference representation of the differential equation by difference approximations. Here the method of characteristics, the central difference scheme and the wind-up scheme, will be discussed.

The method of characteristics is a simple and very flexible method and is implemented in many versions. Basically the method searches for solutions from a given starting point, the initial value, keeping the direction along the so-called characteristics line of the problem. This line is the natural solution for the given problem. The most serious limit of this method is the fact that the method cannot solve problem types with one unknown boundary condition. This is the case for the pipe flow problem. Hence the method ought not to be applied here. However, (Hilmer, F., 1996), (Hilmer, F., Vajen, K., Ratka, A., Ackermann, H., Fuhs, W, and Melsheimer, O., 1999) apply the method for strongly dynamic flow rates in solar collectors and show better results than for other methods.

The most common scheme is the Central Difference Scheme. Here the unknown value of a given point is calculated on the values of the time step beforeinvolving the points symmetrically to the right and the left of the unknown point. This can be represented by a so-called calculation molecule where the "smiley" represents the unknown point to be computed. Unfortunately the method assumes knowledge of the grid point values on the right boundary to the domain, which is not the case in the flow problem, namely where the outlet temperature of the pipe is the unknown.



In the following we will take a look at the most obvious numerical methods for solving this problem type and the numerical artefacts related to these techniques.

7.2.2 The upwind approach – A possible solution

Similar to any differential scheme applied above a grid is imposed onto the "problem" domain. Typically a regular grid, on the upper half-plane of the domain, similar to Figure 17, with step lengths Δx in the space domain and Δt in the time domain is applied. The indices "m" and "n" are applied, respectively, as sketched in Figure 20 and the time step counted by "i".

For the upwind method we find the following difference scheme and method characteristics.

Table 10. Finite difference scheme and characteristics for the upwind method.

Difference formulation for time derivative	$\frac{\partial u}{\partial t} = u_t \approx \frac{u_i^{m+1} - u_i^m}{\Delta t}$
Difference formulation for space derivative	$\frac{\partial u}{\partial x} = u_x \approx \frac{u_i^m - u_{i-1}^m}{\Delta x}$ for $k_i^m < 0$ $\frac{\partial u}{\partial x} = u_x \approx \frac{u_{i+1}^m - u_i^m}{\Delta x}$ for $k_i^m \geq 0$
Stability	$\frac{\Delta t}{\Delta x} \leq \frac{1}{k}$
Error	$e = O(\Delta x) + O(\Delta t)$

We find from the Table 10 that the upwind scheme is of first order accurate (the terms $O(\Delta x)$ and $O(\Delta t)$ are of first order) and stable for the given condition only. More about this later in this section.

1) Introducing another notation, describing the computed value, $\hat{u}_i^m$ for the grid point (i,m), instead of the "accurate" value, u_i^m, in a grid point. 2) Substituting $\mu_1 = \frac{k \cdot \Delta t}{\Delta x}$ and 3) solving for $\hat{u}_i^{m+1}$ we find

$$\begin{aligned} \hat{u}_i^{m+1} &= (1-\mu_1)\hat{u}_i^m + \mu_1 \cdot \hat{u}_{i-1}^m + \Delta t \cdot g^m \quad &, \text{for } k < 0 \\ \hat{u}_i^{m+1} &= (1-\mu_1)\hat{u}_i^m + \mu_1 \cdot \hat{u}_{i+1}^m + \Delta t \cdot g^m \quad &, \text{for } k \geq 0 \end{aligned} \tag{23}$$

Note that due to the equation notation in (21) the sign convention is opposite to the notation in (Barker, V. A., 1998).

Using the matrix-notation for the equation of the whole system, $\mathbf{u}^{m+1} = \mathbf{A}\mathbf{u}^m + \mathbf{b}$, where the matrix A is a bi-angular matrix with zeros in all other elements and introducing further the constants and $\mu_2 = \alpha \cdot \Delta t$ and $\mu_3 = \alpha \cdot \Delta t \cdot u_0$, we find for the given case with positive advection parameter

$$\hat{u}_i^{m+1} = (1-\mu_1-\mu_2)\hat{u}_i^m + \mu_1 \cdot \hat{u}_{i-1}^m + \mu_3 \tag{24}$$

$$\hat{\mathbf{u}}^{m+1} = \begin{bmatrix} (1-\mu_1-\mu_2) & & & \\ \mu_1 & \cdots & & \\ & & \cdots & \\ & & \mu_1 & (1-\mu_1-\mu_2) \end{bmatrix} \hat{\mathbf{u}}^m + \begin{bmatrix} \mu_3 \\ \mu_3 \\ \mu_3 \\ \mu_3 \end{bmatrix} \tag{25}$$

Looking at the "calculation molecule", the upwind method involves three points as indicated in Figure 18 by the encircled molecule. Except from the point to be calculated, all the involved points lie at the previous stepand are known at the current time of computation. Hence the method is <u>explicit</u>. Due to the fact that there is no symmetry around the point to be calculated, the upwind method is one-sided, has a direction dependent on the constant k. Mistakes in the choice of direction are easily found– the results get chaotic for all circumstances.

Unfortunately, the upwind-method introduces some numerical artefacts. Before examining these artefacts and the computation results, some introduction to theoretical basics is necessary for the interpretation and understanding of the results.

As we found above, the differential problem is, due to discretization by numerical methods, re-defined to difference problem. The background for such discretization can be found in Taylor-series that state:

$$f(x) = f(a) + f'(a)(x-a) + \frac{f''(a)(x-a)^2}{2!} + \ldots + \frac{f^{(n-1)}(a)(x-a)^{n-1}}{(n-1)!} + O(\delta^n)$$

where f' is the first derivative of the function f and $O(\delta^n)$ is the remainder when restricting the Taylor series to a certain number of terms.

The numerical approximation of differentials by difference terms is based on such Taylor-series approximation, typically involving up to two terms only. The reminder then gives a good estimate of the error made, by applying the approximation, the so-called truncation error. By rearranging the chosen approximation, the difference terms of e.g. Table 10 are generated and error estimation derived.

The stability of numerical methods is also mentioned in Table 10. For all numerical methods, if the stability conditions are not met, the results are not converging with increasing number of time steps. The results 'blow up', get chaotic and are useless as we will investigate later in this presentation.

The stability of a given method is based on a Fourier-series term, the "von Neumann" stability analysis. Before examining the stability for the upwind method, we introduce the so-called Courant-number, Cou, by

$$Cou = \frac{k \cdot \Delta t}{\Delta x} \tag{26}$$

The Courant-number can be interpreted as the distance of the advective flow per element in the space domain. It seems reasonable that the flow must not be larger than the length of a single space-interval. Rearranging the stability condition to the form of the Courant-number, we get the stability condition, $Cou \leq 1$. If the advective displacement is larger, the methods applied in this study are not able to predict a reasonable value for the dependent variable.

The result from the stability analysis for the problem defined in equation (23), an advection-diffusion problem with source (term involving α), we find that the stability is achieved if $-\frac{\alpha}{2} \leq Cou \leq 1 + \frac{\alpha}{2}$. We find from this that 1) the method is not unconditionally stable and 2) that the source term, α, stabilises the method by $\alpha/2$.

For the upwind scheme, there are conditions that meet the stability constraints, but lead to imperfect results, called numerical diffusion. The term diffusion is chosen due to the similarity of the artefact to real diffusion, as we will see in the following. Numerical diffusion appears due to the imperfect difference approximation, similar to the truncation error due to imperfect representation of numbers in the computer notation.

7.2.2.1 Examination of the wind-up method

In the following we will investigate and discuss numerical diffusion based on an example implemented in the simulation environment MATLAB®. For this investigation we superimpose different influences, so-called boundary conditions, onto the example case.

The case is one metre of pipe with a certain diameter and a given thermal capacity in fluid and pipe. Different flow patterns (flow and temperature at the inlet of the pipe) and conditions for the pipe surroundings are assumed.

Explanation of the figures below: The figures applied are, in the first case, rather complex to read. The 3-dimensional plot shows an axis lowest, representing the space domain, the length of the pipe. The axes on the right side of the plots represent the time, going from back at the starting time to front at the end of the simulation. The heights of the plot and the colour of the plane represent the temperature value at a given time and place.

Experiment 1:

If we start with the simplest case, where both advection and diffusion are zero, no change of the dependent variable - the outlet temperature - is found. The temperature in the pipe is not changing in time and along the pipe. This result is true and shows no numerical artefact.

Experiment 2:

In the next experiment, the advection is zero (no flow), but the surrounding leads to heat losses. The results show that the pipe temperature changes in time from the initial condition to the ambient condition, but no temperature change along the pipe is visible. The speed of change depends on the diffusion parameter. Also this simple case is modelled correctly.

Experiment 3:

Imposing constant flow by a constant advection parameter value but assuming no heat loss, we find the temperature development as visualised in Figure 19. At the upper end of the plots, the initial temperature distribution is plotted as a "wave" with low temperature on the inlet (left side of each plot) and on the outlet (right side). In the centre of the curve the temperature is rising slowly up to a maximum and decreasing again towards the outlet.

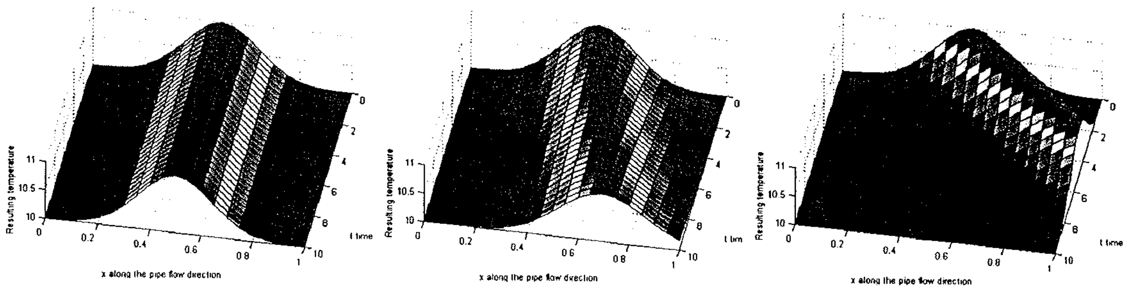


Figure 19. Three examples of pipe-flow calculation results by the numerical upwind method. For all calculations an initial condition described by a Gauss distribution is applied. Calculations begin at the back of the drawing, running with time to the front of the plot. The boundary condition, the inlet temperature on the left side of the plot, is constant and chosen not to affect the development of the initial "wave".

Left figure: No flow condition.

Middle figure: k=0.02 (little flow).

Right figure: k=0.1 (large flow).

In Figure 19, three cases of advection parameter values are compared. In the left figure, the flow parameter is zero, growing in the centre figure and getting almost too big in the right figure. The results (The time is running from back to front) for $k=0$ (no flow, left figure) show that the initial shape "wave" is not moving with time as expected. For a small flow value (Figure centre) the "wave" is moving slowly to the right boundary, the outlet. For larger advection parameter the wave moves fast to the outlet. If the parameter k gets too large the mass to the pipe leaves the pipe during one single time step. This phenomenon is often misinterpreted as "numeric diffusion", but ought to be classified as useless "chaotic" results as shown in Figure 20.

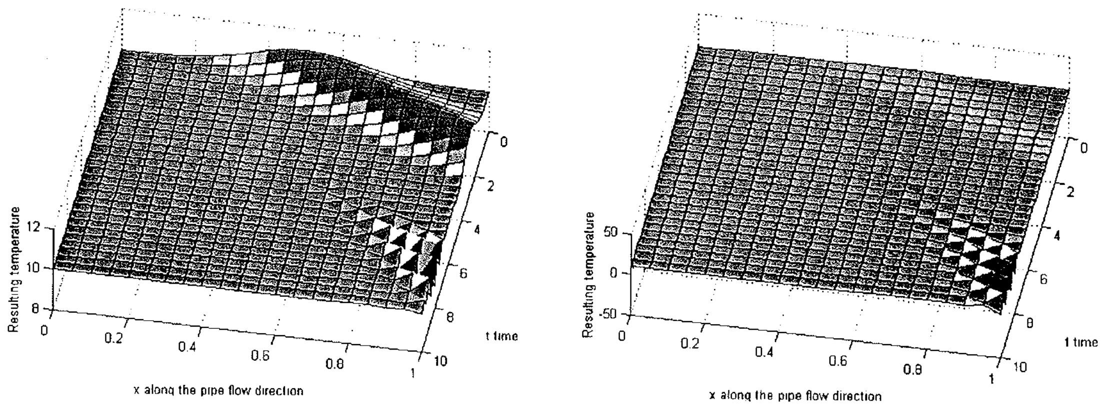


Figure 20. Results for failed computations. Note: The temperature amplitude is sized differently which gives a strong hint for instability (non-convergence).

Left figure: The limit of computation is reached.

Right figure: The limit for stable computation is crossed. No logic can be seen anymore.

We find in Figure 20 to the left that the wave is still visual, but the first artefacts are seen at the outlet. In the right figure the artefacts take over. This is here called chaotic behaviour. This chaotic behaviour of the temperature estimation for the upwind method can be explained by the stability criterion in Table 10 that is given by $\frac{\Delta t}{\Delta x} \leq \frac{1}{k}$. This means that the stability is dependent on the advection parameter, k. For growing values of k, the stability gets more critical. In other words: For growing k (stronger flow) and given Δx, the time step must be inverse proportional to the advection parameter. Smaller time steps must be chosen. Such conditions ought to be escaped/avoided by choosing other numerical techniques.

For different advection parameter values as shown in Figure 20 we find:

For $k=0$ the stability is infinite which seems to be the case, running under these conditions for a very long computation time. No diffusion is visible.

For $k=0.02$ the right hand side of the stability condition gets 50. If we choose a pipe of one metre's length and $n=10$, we find $\Delta x = 1/10 = 0.1$ and we get from the stability condition that present steps must be below 5 seconds.

Running the computations for 100 seconds, we have (See definition in Figure 18) $m>20$. Computations show that the numerical artefacts first apply to $m=16$, a little lower than described in the stability criterion.

In the next experiment both advection (flow) and diffusion (heat loss) are imposed simultaneously. We typically find results as shown in Figure 21.

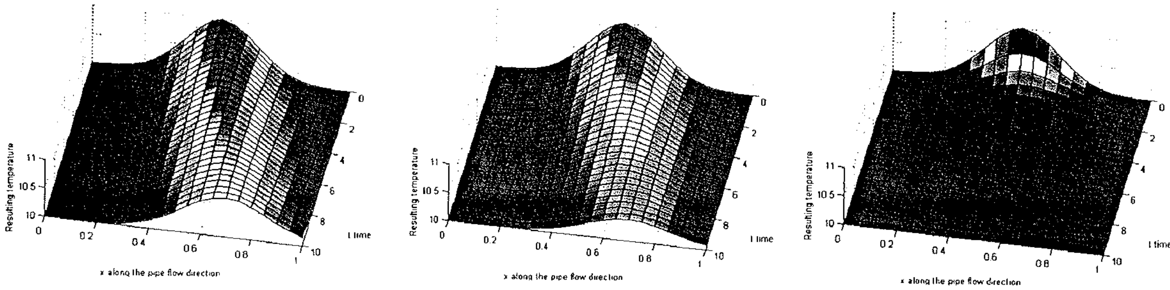


Figure 21. Three examples of pipe-flow calculation with heat loss computed by the numerical upwind method. For all calculations an initial condition described by a Gauss distribution is applied. Calculations begin at the back of the drawing, running with time to the front of the plot. The boundary condition, the inlet temperature on the left side of the plot, is constant and chosen not to affect the development of the initial "wave".

Left figure: A rather small diffusion parameter is chosen. Small heat loss and little declining height of the "wave".

Middle and right figure: For larger diffusion parameter things get faster.

We see in Figure 21 that the wave is moving due to advection to the outlet (right side) and that the wave height is decreasing due to diffusion with time, also visualized in colour.

Choosing too large values for the diffusion we get a chaotic picture as in Figure 22.

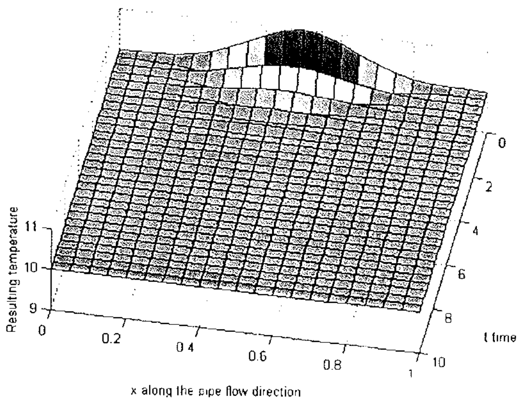


Figure 22. Calculation results for an advection-diffusion case with too high diffusion constant value. The solution gets unstable.

We may find from Figure 22 that the computed values between time steps are "over-shooting" and "under-shooting", like a string that is swinging. This is an artefact of the method and not due to real-world phenomena.

It is worth while mentioning that the diffusion term is damping the characteristics of the advective influence on the method stability as mentioned above. This seems reasonable due to the fact that heat loss damps the "wave"-characteristics of the advective flow.

The computation explains why numerical diffusion has got its name: We see that numerical diffusion for stable conditions decreases the height of a given temperature profile (e.g. a wave height is decreased by numerical diffusion) equal to the effect of diffusion on the same temperature profile.

In the experiments above, the inlet conditions and the boundary conditions are kept constant. In the next experiment these boundary conditions are changed. To get an idea of the response due to the changes, the initial temperature distribution in the pipe is set to a constant value instead of the wave-shape applied before.

Before going into details, the readers must be aware of the meaning of the Courant-number, defined in Equation (23), stating that the ratio between time step and space step times the advection constant must be below one, preferably close to one, otherwise the method will be unstable.

(Pálsson, H., 1997) presents an examination for district heating pipes with changing boundary conditions. In this work it is shown that a temperature front provoked by a stepwise temperature change at the inlet will propagate along the pipe with a very small change in shape. This case is reproduced in the following by a stepwise change of the boundary condition from 20°C to 10°C. In Figure 23 the results for different Courant-numbers below 1 are examined for the given case. Here the view of the plot is changed. We now look from the top onto the space-time plane (inlet on the left side, outlet on the right side and the time "going" from back to front).

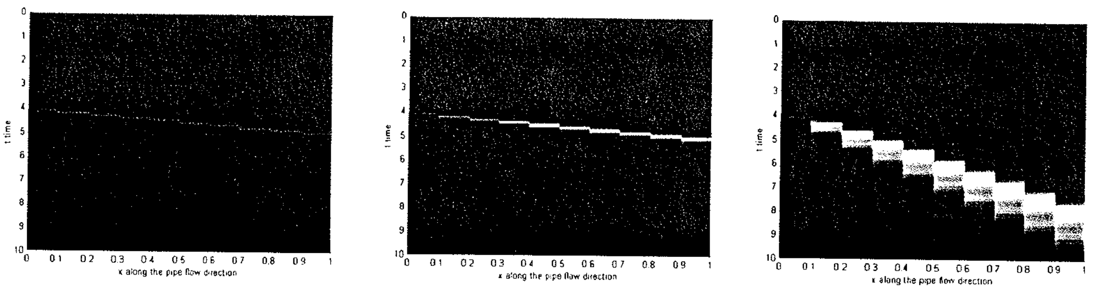


Figure 23. Computation results for constant initial condition and stepwise changing boundary condition.

Left figure (x-t plane): Cou=1: The temperature front defined by the stepwise temperature change is moving from left to right.

Middle figure: Cou = 0.09: Numerical diffusion is visible.

Right figure: Cou=0.02: Numerical diffusion gets dominating and leads to wrong results. The temperature profile is flattened as time goes by.

From Figure 23 we find:

For *Cou=1*, the temperature front, defined by the step-change of the temperature, is moving along the pipe with no changing of the step-shape. This is visualised by a sharp edge in the plot. The speed of the movements is naturally pre-determined by the value of the advection parameter, *k*. In the centre plot a slight diffusion gets visible by a changing colour, getting much more expressed in the figure to the right for a Courant-number far below 1.

From Figure 23 we can conclude that artefact and numerical diffusion get larger with decreasing Courant-number. We also know from the stability criterion, that the method is unstable for Courant-numbers above 1.

In real-world applications the advection parameter is changing in time. With respect to the stability criterion the changes must be reflected by the step-sizes, often called "methods with variable time-steps". This must be kept in mind when building numerical tools for flow problems.

The question is now if there are other alternative solutions to the problem that are not suffering from numerical artefacts. This will be discussed in the following section.

7.2.3 Alternative numerical approaches

Two main sources of alternative numerical methods for the flow problem are found, (Barker, V. A., 1998) a researcher in numerical techniques, and (Pálsson, H., 1997), tackling the problem as a modeller of dynamics in district heating.

(Barker, V. A., 1998) presents a number of alternative numerical techniques. All of them are based on central difference schemes and involve, in contradiction with the upwind method, a point one step ahead in the x-direction. This makes the methods, as they are presented, inapplicable to the pipe-case where the second boundary condition at the outlet of the pipe is not known. However, the methods are shortly mentioned here:

1. Lax method, a first-order method that improves the stability criterion to be the same for any sign of the advection parameter, *k*, and also improves the truncation error not to be dependent on both Δx and Δt, but only on Δx.
2. Lax-Wendorff method, a second-order method, improving the truncation error to the square of Δx with similar stability conditions as the Lax method.
3. Leapfrog method, a second-order method that improves the truncation error to the second order of both Δx and Δt and similar stability conditions as the Lax-method.
4. Two-step Lex-Wendroff method, where the first step is a Lax method and the second a leapfrog method. The truncation error is of second order with similar stability conditions as the other methods.

From this overview we find that at best the stability condition can be independent of the sign of the advection problem but not of the change in amplitude. Hence there is no solution in our case. Also the methods claim knowledge of the outlet temperature which is not known in our case.

(Pálsson, H., 1997) who worked with heat loss modelling of district heating pipes, approaches the problem of numeric diffusion from another direction, concentrating on different problem descriptions. Pálsson presents two modelling approaches applied in district heating modelling and pipe modelling in general, the node method and the element method. To make the summary as complete as possible, a third method, the "plug-flow" model, is added by the author. Note that the description by Barker and the one by Pálsson deal with the same problem, but with a rather different scope of generality. Therefore an effort is made here to make the presentation coherent.

7.2.3.1 The node method

The node model is, among many others, applied by (Bennonysson, A., 1991) for district heating pipe modelling and (Dutré, W. L., 1990), (Qin, L., 1998) and (Rahbek, J. and Svendsen, S., 1995) for pipe modelling in solar heating applications.

In the node method the temperature in a pipe is represented as node temperatures for the involved components, typically the pipe and the fluid. A sketch of such a node representation is given in Figure 24.

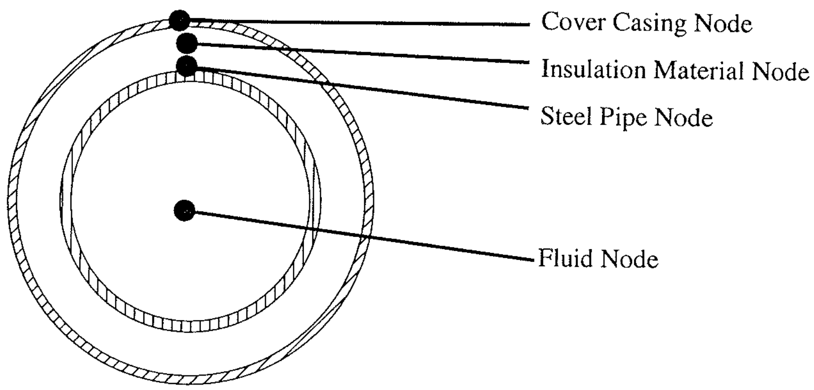


Figure 24 Sketch representation of the Node-Method for a pipe flow problem. The pipe model consists of a few layers of different materials (cover, insulation and pipe) and the fluid running in the pipe.

The nodes represent the temperatures for the whole pipe length. The time-dependency for the given nodes is strongly determinated by the thermal capacity of the material. Computations are made by assuming an average temperature along the pipe. From heat and mass balances we find the following differential equation.

$$C_e \cdot L \cdot \frac{d\overline{T}}{dt} = \dot{m} \cdot C_p (T_i - T_o) - U_p \cdot L \cdot (\overline{T} - T_a) \tag{27}$$

where $\overline{T} = (T_i - T_o)/2$ is the mean temperature of the pipe in °C,

- T_i inlet temperature in °C,
- T_o outlet temperature in °C,
- L length of the pipe in m.

Rearranging equation (27) to the form of (21) we find

$$\frac{d\overline{T}}{dt} = k_n (T_i - T_o) - \alpha_n (\overline{T} - T_a) \tag{28}$$

Notice:

1) The temperature is the average over the whole pipe length, estimated as e.g. linear or exponential decreasing function.
2) The partial differential equation is redefined to an ordinary differential equation by the average-temperature assumption.
3) The parameters have an index to emphasize the distinctions to the problem description in equation (21).

7.2.3.2 The element method

The element method is applied by (Bøhm, B., 1994) and (Bennonysson, A., 1991).

Contrary to the node method, in the element method the pipe is subdivided parallel to the flow direction by *n* elements. Each element represented by a single, uniform temperature, $T_{e,i}$, for the i'th element. One can say that each element is represented by a weighted sum of the temperatures from the node formulation. A sketch is presented in Figure 25.

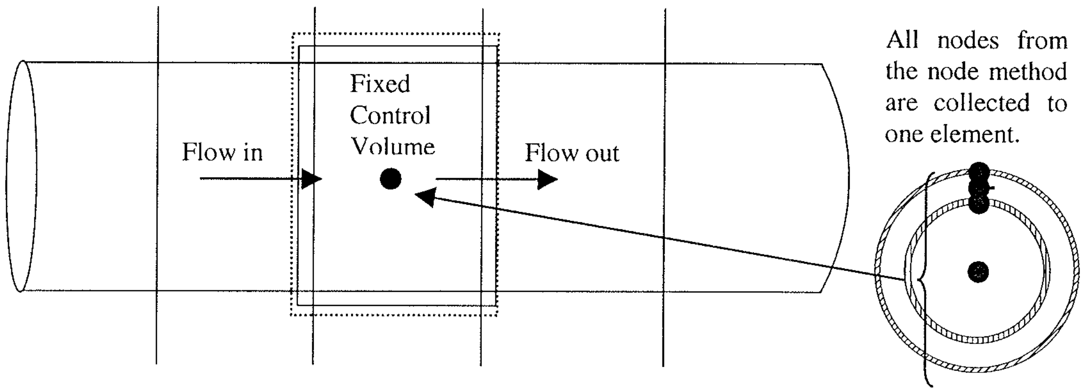


Figure 25 Sketch representation of the Element-Method for a pipe flow problem. The pipe is subdivided into n elements parallel to the flow direction. Each element consists of a single temperature. The elements are fixed and the flow in the pipe is traversing the elements.

From an energy balance for an element we find the energy equation

$$C_e \cdot l_i \cdot \frac{dT_i}{dt} = \dot{m} \cdot C_p (T_{i-1} - T_i) - U_p \cdot l_i \cdot (T_i - T_a) \quad (29)$$

where
- t time in s,
- l_i the length of the i'th element in the pipe in m,
- $\dot{m}$ mass flow rate in m/s,
- C_e heat capacity of the element (pipe and fluid) in J/(m K),
- C_p heat capacity of water in J/(kg K),
- T_i temperature of i'th element in the pipe in °C,
- T_a ambient temperature in °C,
- U_p heat loss coefficient of the pipe in W/(m K).

Note: The equation derived from equation (21) by discretizing the time domain. From these findings we can conclude that the upwind method described above can be classified as an element method.

7.2.3.3 The plug-flow method

The plug-flow model is in short described in (Qin, L., 1998) and applied for large-scale solar heating modelling by (Isakson, P. and Eriksson, L. O., 1993).

A sketch is presented in Figure 25.

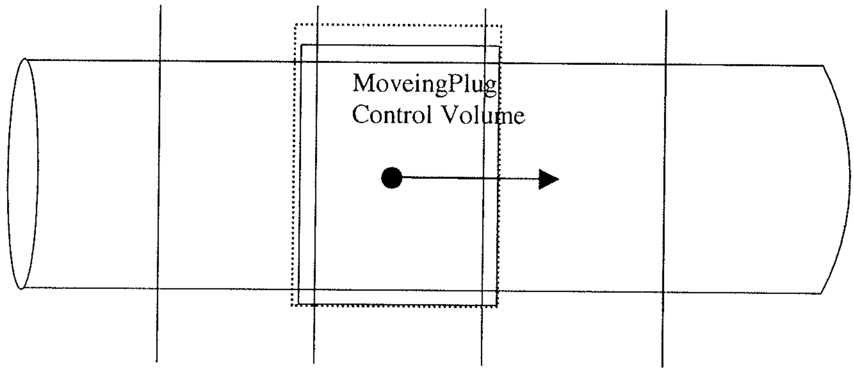


Figure 26 Sketch representation of the Plug-Flow-Method for a pipe flow problem. The pipe is subdivided into n "virtual" plugs parallel to the flow direction. Each plug consists of a single temperature node. The plugs flow in the direction of the flow along the pipe with a weighted velocity dependent on the involved thermal capacities.

Similar to the element method, the plug-flow method subdivides the pipe into parts (plugs) in the flow direction. Contrary to the element method, the control volume is moving. The velocity is dependent on the involved thermal capacities, typically the capacity of the fluid and the pipe. The plug-flow velocity is then damped by the pipe capacity. In many cases the boundary conditions are kept constant for a plug during the whole passage of the pipe. This is done due to numerical reasons and leads to uncertainties of the method.

From the heat and mass balance for a given control volume we find the partial differential equation

$$V\frac{\partial T}{\partial x}+\frac{\partial T}{\partial t}=U_p\left(T_a-T\right) \qquad (30)$$

where $V=\dot{m}\cdot C_p/C_e$.

It is easy to see that the method is very similar to the element method. In the following the similarities and diversions are extracted and discussed.

We se from the model descriptions above that the problem description in equation (21) can be categorised as an element method. We find that both element and plug-flow methods subdivide the pipe into segments/elements along the pipe. The two methods are different in the way the involved capacities (from fluid and pipe) are handled and "what" is moving due to the flow of the medium. In the element method the fluid is traversing the control volume, as in the plug-flow method the control volume, the plug, is moving. The velocity is adjusted on the involved capacities. The plug flow model solves the capacity challenge by letting the advection parameter reflect the different capacities in one single value. The result is a single advection parameter that defines a new element with a "numerical" flow velocity, *V*, the plug velocity. Here from the naming of the method. In the element method, the individual capacities are solved by a system of differential equations. According to (Barker, V. A., 1998), on the one hand, all the above-mentioned difference method can immediately be extended to hyperbolic systems, which arise from a set of systems described by the advection-diffusion problem. On the other hand, Barker states that "the upwind methods are unsuited to problems with values of both signs." Here it would be relevant to focus on the fact that the upwind method is not applicable for any kind of problem.

Note: Readers especially interested in the solving of a set of flow problems simultaneously are referred to (Barker, V. A., 1998).

Accepting the fact that the element method and the plug-flow method are very similar, we can conclude that the node method basically divers from this element approach. Here the two-dimensional problem is in focus from another point of view. Instead of subdividing the problem in the flow direction, the division/discretization is made in the direction of changing capacities. One node for the flowing material and one for each involved pipe part, the steel pipe, the insulation etc. The interpolation along the pipe is not solved by difference approach but rather by assuming a function for the independent variable along the space domain. Different node methods require different functions or methods.

For all methods the two-dimensional problem is now re-organised to be a one-dimensional problem in time. The methods for solving such problems are similar. According to (Pálsson, H., 1997) and also to own experiences, the most common method applied in literature is the upwind method.

Pálsson examines four methods where the two of them are connected to an element method and the two of them to the node formulation. The most important finding from this work is that both the node and the element methods can be improved by applying a quadratic interpolation scheme instead of the first-order interpolation that is applied by early versions of the methods. An example of the quadratic approach to the element method is presented in (Leonard, B. P., 1979). Pálsson presents a corresponding node method. Using the terms introduced above, a quadratic interpolation technique involved four cross points in the timestep domain, compared to the two involved points in the upwind method, shown in Figure 18. The methods show no severe artefacts for Courant-numbers below 1, which is a relevant improvement. The methods should, according to the sources, have accuracies of third order with respect to Δx. The stability condition is still similar to that of the upwind method.

Note: For strong dynamic modelling of flows Hilmer has presented a rather interesting study with surprising results, (Hilmer, F., 1996) and (Hilmer, F., Vajen, K., Ratka, A., Ackermann, H., Fuhs, W, and Melsheimer, O., 1999). Here a characteristic method is investigated with high accuracy and stability.

7.2.4 Discussion and conclusions

In the current section, a physical problem for flow and heat loss in pipes is modelled mathematically as a first-order hyperbolic differential equation. For the solving of the problem, numerical difference approaches are investigated. It turned out that the problem would normally be solved by a Crank-Nicolson method, which is fast and accurate. Due to the fact that one boundary condition at the outlet of a pipe is not known, the method cannot be applied. Hence the upwind-scheme is applied by most solutions to one-directional flow problems. The upwind model is described and its numerical characteristics investigated. The main problem for the method is the demanding stability criterion that is dependent on both the time and the space discretization. Hence the method suffers from numerical artefacts. Alternative solutions are known and widely applied. Unfortunately all methods show worse numerical diffusion than the upwind method. Methods based on quadratic interpolation, independent of the formulation as element or node method, give realistic results with almost no numerical diffusion.

The final conclusion of the thesis in the introduction is: 1) All numerical techniques suffer from numerical artefacts. 2) There are numerical methods that diminish the numerical artefacts to an acceptable minimum. Examples are mentioned above.

From the reflection on numerical methods we are able to conclude that computation of flow in pipes can be handled by a number of methods. As we will see in the following, the plug flow model is applied in the district heating pipe model of TRNSYS. Based on the numerical findings we are able to conclude that this model can be stable if the stability criterion is respected. An examination is presented in Figure 35.

8. THE TRNSYS-IMPLEMENTATION – A LOAD GENERATOR

In this section, an attempt is made to prepare a load generator including the most important load component and input parameters. The objective of this effort is to build a tool that can be used for the generation of realistic load profiles for different central heating systems. These load profiles can than be applied by other computation and simulation models. The model is designed to be adjustable by connecting input data files of different sources and by tuning a set of model parameters.

Due to the wide application and the flexibility of the computer simulation environment, TRNSYS®, in the field of solar plant modelling, this tool is chosen for the implementation of the load generator, even though an implementation in e.g. MATLAB® would be wider applicable.

In this section the implementations of the individual heat load components are presented in detail, followed by a description of the overall model, combining the component models to a load generator. Estimates on the validity for the generated data are presented in the relevant sections. A final evaluation and comparison of the generator with other methods will be placed in Part 3.

8.1 Space Heat in Buildings

The space-heating model implementation presented here is the third of a series utilised by the author during the current ph.d.-study. The first implementation is based on a European Research Project under the Altaner programme (Berger, R., 1997). The drawback of the application of the given load profiles is that the model description is missing and hereby the uncertainties rather large. Hence the reproduction is impossible. However the load profiles from this attempt were, due to different reasons applied in the previous work by the author, (Heller, A. and Dahm, J., 1999).

A second attempt is made in connection with a Master Thesis by (Laustesen, J. B., 1999). The results are partly published in (Laustesen, J. B., Svendsen, S., and Heller, A., 2000). A building model, representing a building according to the Danish Standards from 1995, was prepared in the thermal building simulation program TSBI3, (Johnsen, K., Grau, K., and Christensen, J. E., 1993). Based on this reference building two futuristic low energy buildings were modelled with 60 and 30% respectively of the heat demand of the referencebuilding.

The final implementation, presented here, is based on current work done in a co-operation project under the International Energy Agency (IEA) under the Solar Heating and Cooling Programme (SHC), Task 26, "Solar Combisystems". The choice to base the current work on this co-operation is manly that the communication of the methods applied and the findings found is made easier and that the results are comparable with other work. I hope that the methods and models will base a common platform for work similar to the work here involved. Hereby wasting time on discussions on the assumptions for modelling is shortened or even avoided. This is one of the main reasons for the rather comprehensive effort in the load modelling by the author. The drawback of the procedure is unfortunately that the models may change during the ongoing IEA work and that the documentation of the model has not been published in a final version yet.

The "Task 26" building model is in detail documented by (Streicher, W., 2000). The TRNSYS-tool PREBID is used for the definition of the building. PREBID prepares a set of output text files that are used by the overall TRNSYS-model. From this resulting building component model the heat demand for heating the building is estimated in chosen timesteps. The necessary heat demand is satisfied by a radiator system, implemented in the Task 26 work in the TRNSYS-IsiiBat tool, re-implemented in a TRNSYS-PRESIM tool for our own simulations by my colleague Louise Jivan Shah. The general models are then run with Danish climatic conditions to generate space-heating profiles for Danish buildings.

Two building types are implemented, a single-family house and a multi-family house. The latter is not applied in this work.

The building is designed as a two-storey house with a ground area of 70 m^2 with the heat insulation properties as presented in Table 11.

Table 11 Key values for the single-family building model in three insulation classes, applied in the current work.

Description	**Units**	**Values**		
Common for models				
Type		Single-Family Building		
Ground Area	m^2	70 (10 x 7)		
Stories		2		
Orientation		South		
Design		massive wall (Gypsum, Bricks, Insulation, Plaster)		
Window areas	m^2	East 4, West 4, North 4, South 12		
Other gains		3 persons (170 W), other gains 700 kJ/h		
Ventilation/Infiltration	h^{-1}	0.4		
Shading devices		none		
Insulation Classes	kWh/(m^2 a)	30	60	100
U-values Walls	W/(m^2 K)	0.071	0.266	0.532
U-values Roof	W/(m^2 K)	0.070	0.219	0.494
U-values Ground Floor	W/(m^2 K)	0.118	0.196	0.546
U-value Windows	W/(m^2 K)	0.4	1.4	2.8
g-value Windows	W/(m^2 K)	0.408	0.589	0.755

For the space-heating profile generation the building model is inserted in an overall space-heating model in the TRNSYS-tool, PREBID (see Figure 27, label "Building Model").

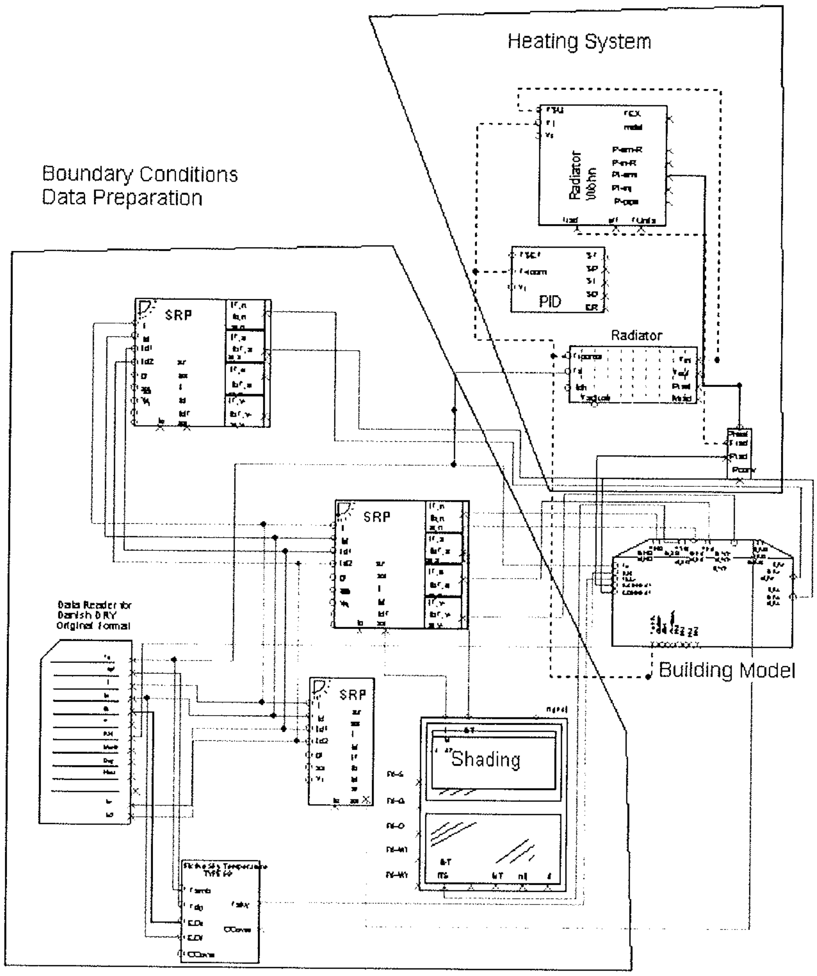
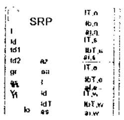
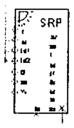


Figure 27 PRESIM representation of building model and heating system. (Only the most relevant components are visualised.)

The building and heating system model from Figure 27 consists of the "Boundary Conditions", the "Heating System"-model and the "Building Model".

The <u>boundary conditions</u> are the climatic data defined in text files, e.g. the Design Reference Year data set. This data is prepared for the different orientations of the involved planes, e.g. roof, walls etc. by so-called "Radiation Processors" visualised by the following two symbols:





The prepared radiation data is then used as inputs to the physical models of the radiation heating and the building heat loss model.

The <u>heating system</u> consists of a static and a dynamic radiator model and a controller for operation control purposes.

The <u>building</u> is represented by a single component only, labelled "Building Model".

The space-heating model generates two outputs, a summary of monthly data and a load file with hourly data to be applied by other applications as input data, here the overall load model described later in this work.

For the three insulation classes presented above the following final load profiles are generated applying the Danish Design Reference Year. The resulting files can be downloaded at the Internet-address:

http://www.ibe.dtu.dk/forsknin/cshp/building/sh_Load.htm.

Table 12 Space-heating Modules.

Building type		**File name**	**Parameter**	**Yearly heat demand**
Single-Family House, 2 storage, 140 m^2				**[kWh/m^2/a]**
	High heat loss	T26DK100.hr	SH_HighD	130
	Medium heat loss	T26DK60.hr	SH_MedD	69
	Low heat loss	T26DK30.hr	SH_LowD	30
Multi-family Building		missing		

The resulting heat load can be visualised as a time series, showing a strongly fluctuating curve with some annual wave-shape. For comparison of different demands and also helpful for the dimensioning of heating systems in buildings, a so-called "duration curve" can be applied. Here the heat loads are sorted and plotted with high observations on the left side and decreasing values to the right. Note: Duration representations do not reflect the time at which certain values occur.

For the three loads of the Task 26 implementations we find the duration curve in Figure 28.

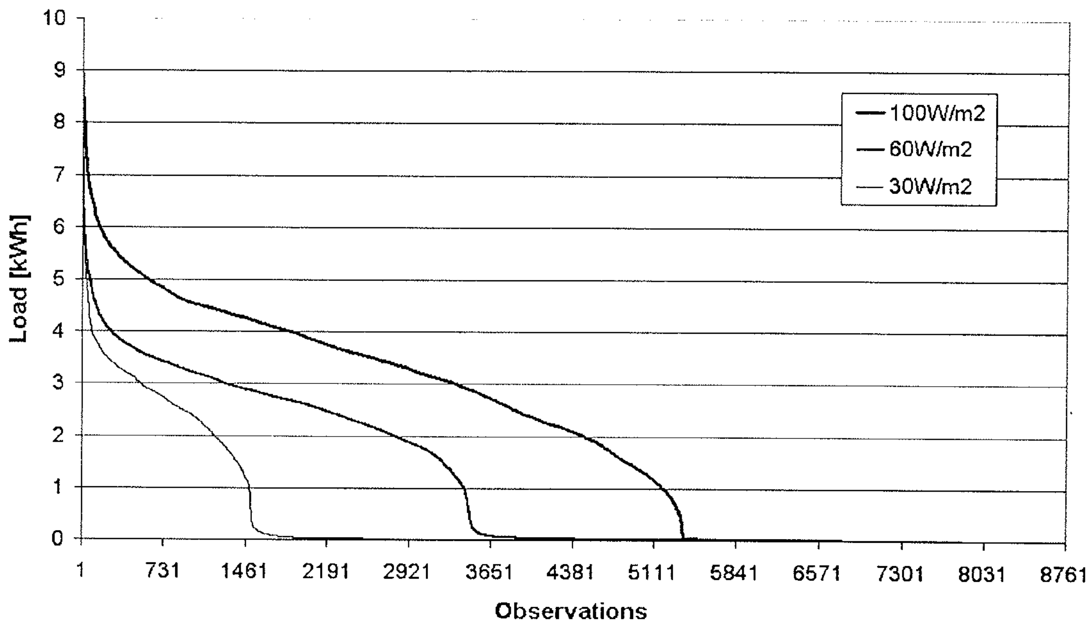


Figure 28 Duration curve for the heat demand of the Task 26 building with three insulation levels under Danish DRY weather conditions.

On the left side of Figure 28 one finds the largest observations, decreasingly ordered to the right side of the plot. We find that all curves show a rapidly decreasing maximum space-heating demand, flatting out in a close to linear shape and ending in a strongly decreasing manner (S-shape). We find, as expected, that the heat demands for the three insulation levels are decreasing – in magnitude but also in number of observations with given demands.

Some general reflections can be connected with this S-shape. Heating systems are designed on norms with implicit assumptions to the maximum load of buildings. From the curves above we find that the "worst case" is only observed for a minimum number of hours during the year. As shown in (Aronsson, S., 1996) for Swedish conditions, it would be wise not to apply the worst-case scenario for the dimensioning of heating systems. Hence revision of the codes in at least Sweden, Denmark and Germany would be recommendable to avoid oversizing of heating systems.

As mentioned above the current space-heating model is the third in a row of three applied models. To enable comparison with findings from older work published by the author and others, the results from the three generations of load data are compared in Figure 29.

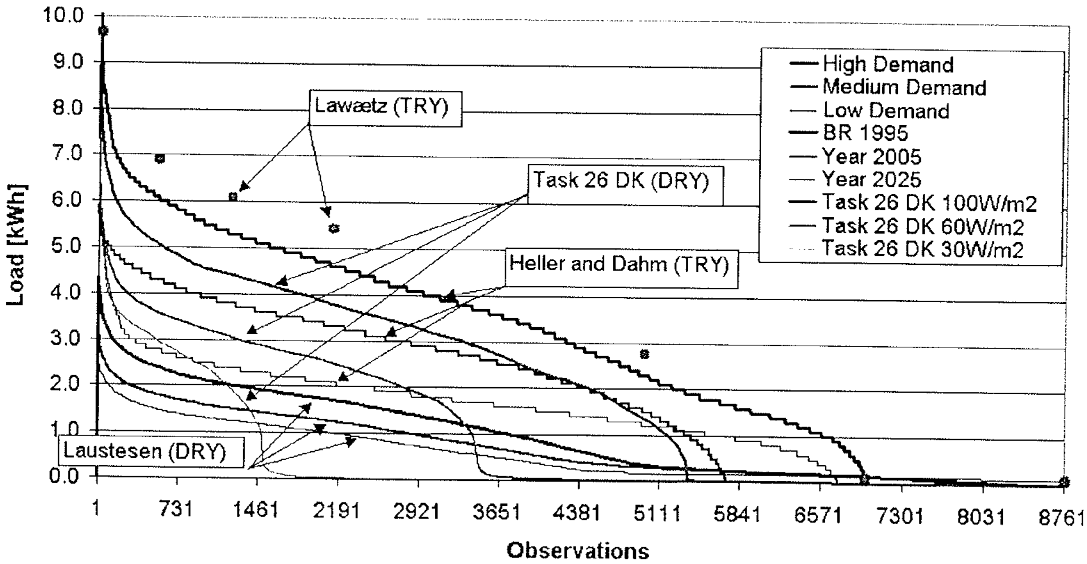


Figure 29 Duration curve for the load profiles applied by the author and others.

The oldest observation (dots) is made by (Lawaetz, H., 1984) and shows the highest load demand.

Three curves are plotted for the heat loads applied by (Heller, A. and Dahm, J., 1999). Here we find the characteristic S-shape with strong decreasing heat demands at highest and lowest observations and a close to linear decreasing demand in between.

We find similar curves for the currently applied space-heating model, labelled "Task 26 DK", but on a lower level.

At the very lower part of the figure, three curves labelled "Laustesen" are representing the load patterns for the buildings applied by (Laustesen, J. B., 1999) and (Laustesen, J. B., Svendsen, S., and Heller, A., 2000).

From the mess of duration graphs of Figure 29 we can extract the following findings:

- The magnitude of loads decreases from older studies to newer work. This can be explained by the fact that the regulations in building codes are imposing stronger claims for thermal insulation of buildings with a resulting decrease in demand.
- The S-shape load distribution is found by all authors, except Laustesen. Reasons for the deviation of the lattercould be 1) that the very low demand wipes out the S-shape 2) that the implementation of the building model affects the shape and 3) that some characteristics of the applied TSBI3 simulation program affects the shape of the curve. More work would have to be done to uncover this systematic deviation.
- The Task 26 models spread over a rather large variety of space-heating demands. The S-shapes for the curves are more accentuated compared to the results of other implementations. This shows that the demands are still rather high, but on the other hand that the number of hours with demand is decreasing. This again indicates that a heating system for such buildings is similar to the systems with higher total heat demands but similar peak-loads. Savings can be expected in fuel, but not due to a simpler heating system.
- An important observation is connected to the tools applied for the deriving of the heat loads. It gets clear that the different models show very different profiles in load duration curves. Hence one can assume that the modelling, mathematics and/or numerics are rather different. It would be worth while working on the question what would be the most realistic basic model techniques. The duration curve could be one of the tools for comparison.

From the above findings we can assume, that the findings in (Heller, A. and Dahm, J., 1999) are comparable with the findings in the current work. Due to the absence of very low heat loads for the Task 26 curves, compared to the "Heller-Dahm" implementation, one can expect a tendency of lower summer loads for the current implementation.

The findings by Laustesen cannot be compared directly with the findings in Heller and Dahm due to the rather dramatic deviation in amplitude and shape of the heat load profile. Not to say that the curves are not realistic. The aim of the work was to find optimised central solar heating systems and district heating in a futuristic new settlement – a rather different aim than the current situation of central heating systems. More work would have to be done on these questions.

The findings by Laustesen are systematically different from the TRNSYS-generated load profiles due to a number of reasons, among others that the profiles by Laustesen are produced by another tool, TSBI3 and that the loads are to represent low energy buildings of the future.

Not so important for the current work, but impressive anyway, is the fact that the Lawætz implementation shows a duration curve that can be compared with the findings by the TRNSYS-models.

8.2 Hot-Water Preparation

Modelling of hot-water preparation (HWP) is rather complex and a covering model is not realistic, hence the results are strongly based on the chosen assumptions and simplifications involved in the implementations. Similar to the situation for the space-heating models above, the author applied a series of implementations in previous work.

The first HWP-model was based on work by Dahm leading to the findings in (Heller, A. and Dahm, J., 1999). Here on the one hand a complex, dynamic flow model for the piping, heat exchangers and on the other hand a very simple daily and yearly profile correlation are lumped. The current implementation is an extension to this approach.

A second implementation was in relation to a Master Thesis, (Laustesen, J. B., 1999), basically a variant of the model by (Qin, L., 1998). Here daily, monthly and yearly fluctuation patterns are combined in a spreadsheet computer program to a final HWP-load profile outputted to a text file.

In this third attempt the findings from IEA SHC Task 26, presented in Part 1 of this report, will be implemented in the overall TRNSYS-model. As explained in this first part, the loads for domestic hot water are prepared for buildings involving up to 30-40 units only. For central heating systems the number of users can be much above this figure. The question is now how the large number of consumers influence on the resulting load due to hot-water preparation? To answer this question two investigations will be made in this study: 1) By application of the different load profiles generated by (Jordan, U. and Vajen, K., 2000a) for consumption of 100 up to 3200 litres per hour. 2) By data analysis of the case/s presented in Part 3 for real world district heating systems. Due to the complexity of this second procedure a less advanced method is applied here. The findings from method 1 are compared with the measured data from the cases of Part 3.

In this first investigation of the impact of HWP-models on the total heat load, we assume the number of consumers to be 1250, similar to the Marstal district heating plant, see Part 3. The heat load for HWP is than found by simply multiplying these demands with corresponding factors, leading to a total demand of 1250*100 l/h = 125,000 l/h total water consumption. By this procedure we find the following resulting load profiles presented in Figure 30.

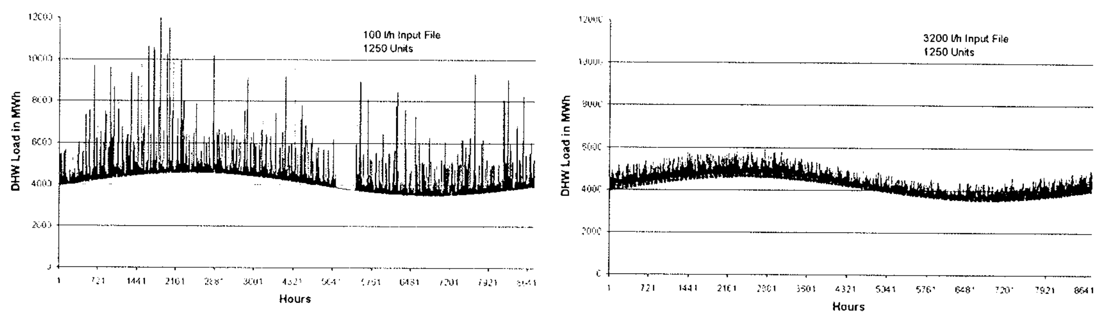


Figure 30 Total heat load for hot-water preparation based on Jordan-algorithm with 100 l/h profile (left plot) and 3200 l/h profile (right plot). By assuming 100 l/h for each building unit, the 1250 building load profile is built by simple multiplication with a respective factor.

From the very different values for the two plots in Figure 30[3] we find clearly that the Jordan-algorithm is doing a good job in avoiding peak effects due to overlapping of many users in a hot-water system. On the left side a resulting load profile based on a profile generated for a single user (a whole family) multiplied with 1250, shows very high peaks for the heat demand during the year. On the right plot the result is presented when using a generated file prepared for 32 units and multiplied by approximately 40. We see that here the peak characteristic is flattened from a maximum amplitude of 6000 down to near 2000 MWh. From this comparison

[3] Note: The applied hot-water load profiles are based on 1-minute values that are averaged to 5-minute values for this work. This procedure is certainly introducing some inaccuracies to the analysis. However, the main points and results are still valid.

we find that it is necessary to include stochastic methods for the distribution of user behaviours, in this case the hot-water consumption. Consequently a load profile for a central heating system must be prepared by applying the Jordan or similar algorithms if the load profile ought to be realistic.

In the load model below the procedure with the large load is applied. Even more realistic results could be obtained if generating HWP load profiles for a large number of users. This is not possible in the time frame of the current work.

8.3 Distribution Net Heat Loss

For central heating systems heat is generated central. Hence heat must be distributed from the production plant to the consumers. A theoretical framework for the modelling of such piping systems is presented in Part 1.

From these theories we are able to argue for the following assumptions, simplifications and the corresponding estimations for the uncertainties of the models:

The reduction of a complex district heating network to a single pipe couple leads to relatively large (> 3K) uncertainties in the modelled temperature at the return pipe. However, if the model is representing a main branch of the net (in the case of central solar heating plants), the simplification will lead to uncertainties of less than 1K.

An error is introduced if a pipe couple is modelled by two independent pipes. The error can be estimated by the equation for the interaction between the pipes, found in the norm and also presented in Part 1 defined by the resistance between the pipes, R_h. However, the error is minimal compared to the error due to simplifications.

In TRNSYS two models are available at the moment. None is implementing the Danish or European norm computations for heat losses in district heating pipes. Both models are single pipe models, not taking the interaction between the supply and the return pipe into account. Both models are implementations of the plug-flow scheme with maximum 25 segments. The Standard-Type 31 is a pipe in air model, as the Non-Standard-Type 80 by (Dahm, J., 1998) implements buried pipe model, taking the interaction with the ground into account, based on the simplification of undisturbed ground temperature discussed in Part 1.

The heat loss per metre of pipe, UA/l, can be found on the basis of (Bøhm, B., 1999a) by the following simplified expression

$$\frac{UA}{l} = \frac{2\pi}{R_s + R_i + R_c + R_g + R_{cp}} \tag{31}$$

where R_s is the thermal resistance for the steel pipe in m^2 K/W,
R_i thermal resistance for the insulation material in m^2 K/W,
R_c thermal resistance for polymer cover in m^2 K/W,
R_g thermal resistance for ground in m^2 K/W,
R_{cp} thermal resistance for the couple pipe in m^2 K/W.

In the Dahm-model the corresponding expression is

$$\frac{UA}{l} = \frac{2\pi}{R_i + R_g} = \frac{2\pi}{\frac{1}{\lambda_{iso}} \ln\frac{d_o}{d_i} + \frac{1}{\frac{d_o}{2}\lambda_g}} \tag{32}$$

where l is the length of the pipe in m,
λ_{iso} thermal conductivity of the insulation in (W/m K),

λ_g thermal conductivity of the ground in (W/m K),
d_o outer diameter of the insulation cover in m,
d_i inner diameter of the steel pipe in m.

It is easy to find that the Dahm-pipe model neglects the resistance of the steel pipe and the cover, which is acceptable. Comparing the resistance term for the ground, R_g, we find the inequality with the Dahm expression on the left and the Bøhm expression on the right of the inequality sign.

$$\frac{1}{\frac{d_o}{2}\lambda_g} = \frac{1}{\lambda_g} \cdot \frac{2}{d_o} \neq \frac{1}{\lambda_g} \cdot \ln \frac{4H}{d_o} \tag{33}$$

where H is the correct depth of the pipe centre in m.

The deviation between the two models is of the order 30% for the thermal resistance of the ground. This influence again is very small compared to the thermal resistance of the insulation material, hence minimal for the total result.

The error applying the TRNSYS Standard-Type 31 can be estimated on the fact that this component model computes the heat loss either on a user-specified constant or varying temperature, e.g. ambient temperature. In the latter case the heat loss will be overestimated by the difference for the ambient temperature changing between –7 and +21°C compared with the average temperature in the ground of 8°C.

Above, in section 7.2, numerical diffusion is discussed in detail. The question here is how this artefact due to application of numerical techniques influences on the heat losses of a district-heating model? For this investigation an accurate MATLAB implementation of a single heat pipe is compared with the TRNSYS-model. It must be mentioned that the underlying numerical techniques are the same for the Type 31 and the Dahm-model, Type 80. Hence results presented in the following, based on the Dahm-model, are also valid for the Type 31-model.

From steady-state computations we find that the uncertainty of the TRNSYS-model is increasing with pipe length, but that even for long pipes the deviation is less than 3%.

For dynamic conditions with changing boundary conditions we find the following results by computations for long single heating pipes. For a flow rate of 12 kg/s and a temperature jump from 100 to 120 degrees we find the following behaviour for the two models. The response due to this temperature change can be seen in Figure 31.

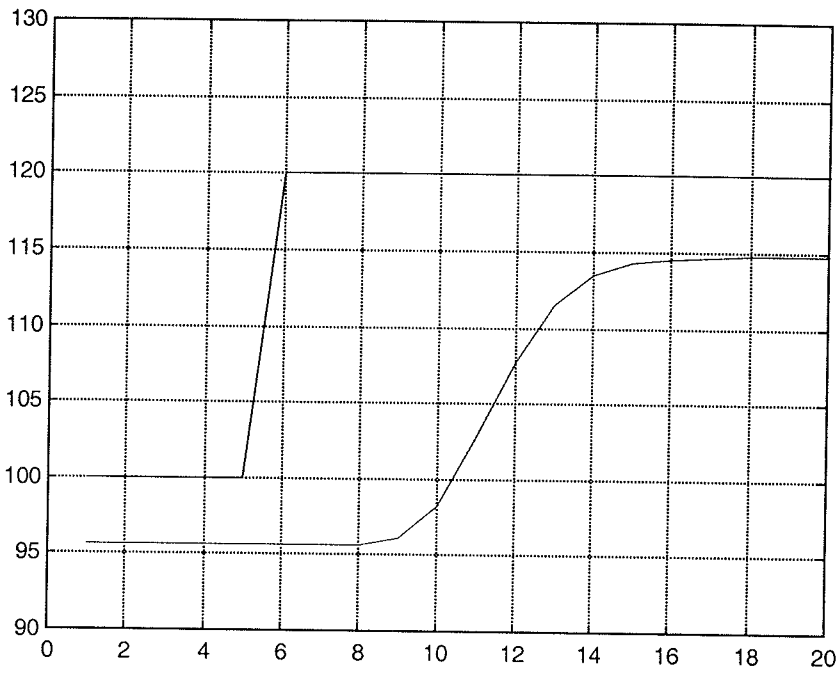


Figure 31. Change in supply fluid temperature (upper graph) and the resulting response (lower graph) for a time period of 20 hours, calculated by the Bøhm-method in MATLAB.

As we see in Figure 31, the supply temperature (upper graph) is changing abruptly. The response at the consumer's, 5 km from the plant, is plotted in the lower graph. We see that it takes some time before the affected fluid is reaching the consumer (approx. 3 hours). The step change is smoothed strongly up to a steady state after 12-14 hours from the temperature change at the supply to a temperature of approximately 115°C. Using alternative numerical methods, the response would happen over a shorter time interval (Pálsson, H., 1997). The question not answered by the cited authors is, at what level the natural diffusion is to be expected. However, for the given case of Figure 31 we find, for the Dahm-model, results dependent on the applied time-step for the computations. The profile for the supply temperatures at the plant and the consumer is shown in Figure 32.

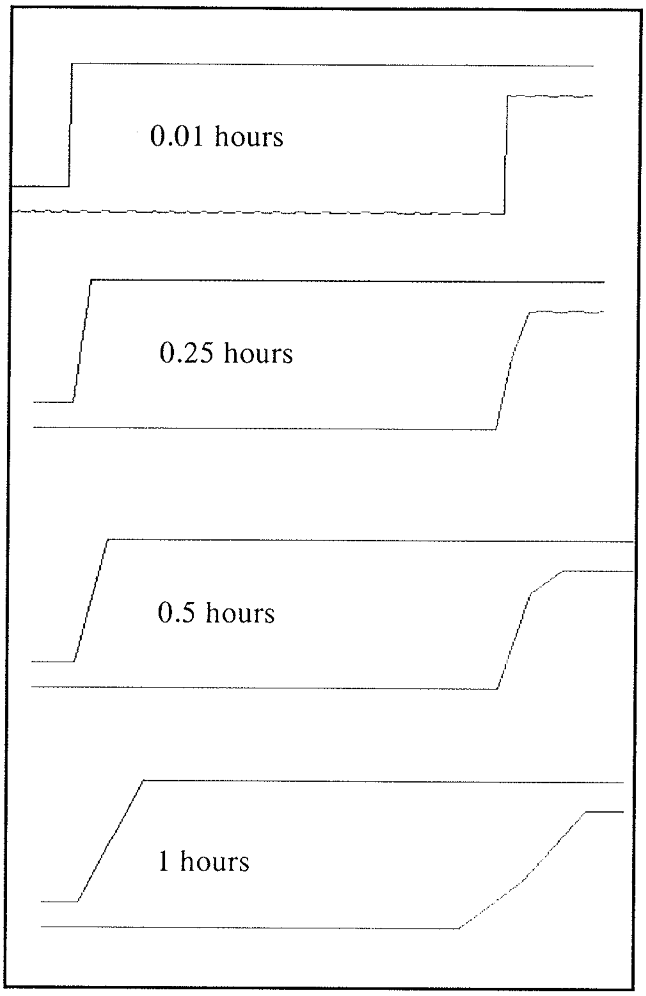


Figure 32. Computation results for the TRNSYS-TYPE 80 performing a step-change in the supply inlet temperature for different numerical timesteps (labelled in the figures).

In Figure 32 the results from calculations of four different time steps are compared. The figure shows four sets of supply and return temperatures for the experiments. On the abses the time is assumed "running" from left to right.

It must be mentioned that change in supply temperature is the same for all calculations, even if the plots show different slope for the supply temperature.

From the computations that led to these results and the plots in the figure, we are able to conclude the following:

For short timesteps the return temperature is increased very rapidly, which is not the case for the computations with long time steps. For long timesteps the return temperature is "smoothened".

It is worth while mentioning that the curves for long time steps are rather surprising. One would expect a "S-shaped" curve as seen in Figure 31, while we find a bowed line curve in the lowest plot of Figure 32. The reason cannot be explained exactly, but is supposedly due to the applied plug-flow scheme in the flow calculations.

Comparing the results of the Dahm-model with the corresponding results of the Bøhm-method, using one-minute time intervals for computations, we find that the Dahm-model leads to a response time of 6 hours, which is 2 hours longer than the Bøhm model. This finding is not surprising due to the fact that a "fast and dynamic" method does not flatten the response orspreads it over a long period. This also agrees with the fact that the Dahm-model reaches the steady-state conditions much faster than the Bøhm-model (+6-8 hours longer transition period). Both methods compute a steady-state temperature after the change of approximately 115°C.

From these findings we can conclude that the flow model for piping in TRNSYS leads to reasonably realistic results. →Therefore the uncertainties involved in heat loss computations are caused by simplifications to the net and less by the above-discussed numerical artefacts.←

8.4 The Overall Load Profile Generator

We have now described the details of the individual implementations of the load components. In this section these components are gathered to an overall load generator model visualised in Figure 33.

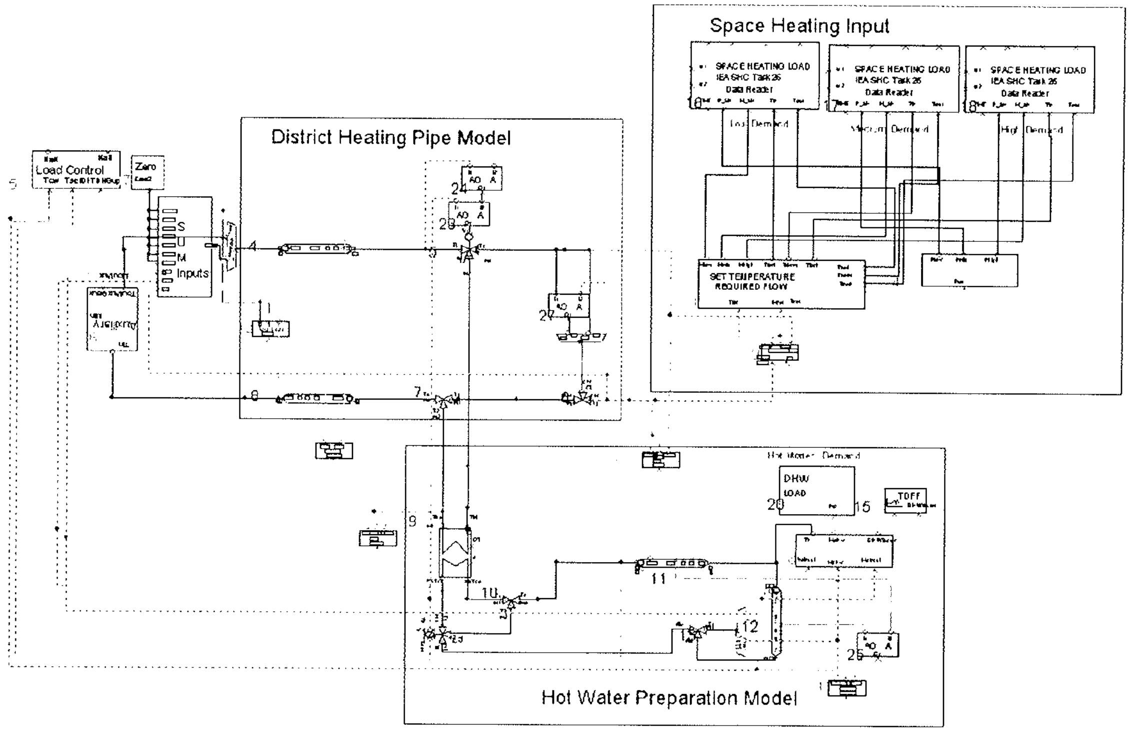


Figure 33 A PRESIM drawing of the final load generator model. The model consists of three parts visualised by squared boxes, the space-heating part, the hot-water consumption part and the district heating part.

Note: Parts of the model are hidden.

The overall load generator (LG) model consists, as visualised by the squared boxes in Figure 33, of three main parts, the sub-model for the space heating, the hot-water preparation and the district heating heat loss model. In the following the load generator model is described in detail.

On the one hand the LG-model includes input data for some of the heat load components, e.g. space-heating and hot-water preparation. These data can be based on measurements or simple assumptions or, as the case here, be generated by dynamic simulations. On the other hand the overall model involves models interacting dynamically as a part of the simulation, generating the final load profile for the whole system.

The LG-model can be adjusted to a certain purpose by a number of parameters and input data sets. By these means the model can be tuned to serve many objectives.

A special model trick is applied in the given implementation. No pumps are applied. The mass flows are controlled by directly forcing flow to the hydraulic components. The drawback of this implementation is that the model can come out of mass balance without warnings. By mass balance control under the development this problem is solved for the given tool.

The district heating pipe network model consists of two heating pipes, represented by the standard TRNSYS component, TYPE 31, and an auxiliary heating equation, for the determination of the minimum heat load necessary to bring the flow medium up to the necessary supply temperature at the main heating plant. Alternatively one could use TRNSYS models for this purpose, but due to the goals of the current load generator, the current implementation causes minimum complexity. Heat loss for the buried pipes are estimated based on an average temperature of 8 degrees Celsius. The total flow is a sum of the individual load components, space-heating, hot-water preparation and, if wished, circulation in the district heating system. The model is prepared to include other influences.

The space-heating model consists of up to three different types of buildings, each of them with different space heat characteristics. The buildings available from the overall model are in the given case Table 12. The number of buildings involved can be controlled by the constant parameters also mentioned in Table 12. Hereby the user is able to mix the building stock to be modelled. The total space-heating load is then computed for the given temperature and mass flow rates by simple means. The resulting mass flow necessary for the given district heating temperature conditions, $\dot{M}_{sh,ist}$, is then found by a simple ratio of the current supply temperature and the demanded supply temperature, as follows $\dot{M}_{sh,ist} = \dot{M}_{sh,soll} \cdot \frac{T_{h,soll} - T_{l,soll}}{T_{h,ist} - T_{l,soll}}$

where $T_{h,soll}$ demanded hot supply temperature in ^oC,
$T_{l,soll}$, demanded hot supply temperature in ^oC,
$\dot{M}_{sh,soll}$ demanded mass flow rate in kg/h.

with indices from German language "Soll" for the demanded values and "Ist" for the current, actual values – a very applicable concept. The necessary flow is "diverged" from the main flow and returned at the demanded return temperature for the space heating, mixed with the other part that has not entered the space heating sub-model.

Similarly to the space heating, the demand for hot-water preparation is found on data file inputs multiplied by the relevant number of consumers. Here the heat is extracted from the district heating flow by a heat exchanger, which is often the case for building sub-stations. The hot-water preparation loop consists of the hot-water consumption computed from data file input, and circulation losses. The loop is equipped with a shunt arrangement to avoid overheating.

The LG-model is able to supply online information from the simulations when running and a set of output to files for later analysis.

PART 3 – A Case Study

9. DATA ANALYSIS FROM A DISTRICT HEATING SYSTEM

9.1 The Marstal Case

Marstal is a small village on the Island of Aeroe in the south of Denmark. The local utility, Marstal District Heating A.m.b.A., servicing 1350 connected mainly single-family and row houses with yearly 27 GWh heat, prepared the network in the late 70ies for low-temperature operation. The heat supply temperature is hereafter brought down to 72°C. The return temperature is about 43°C in the summer and about 35°C in the winter. The total length of the pipe network is approximately 4 km with all piping modernised in the recent years, leading to low heat losses in the distribution system. The control and monitoring system is based on PLC's connected to a PC network. 240 parameters have been monitored since 1997, captured in daily reports on which the current analysis is based. It must be mentioned that Danish district heating (DH) systems run low temperature and low pressure, enabling the direct entering of the flow medium to the buildings for space heating. Hot water is typically heated by tank-internal heat exchangers.

In literature many methods are presented for the analysis of such time-series data, among others: systematic plotting as applied by (Aronsson, S., 1996), simple and multi-regression methods applied by Aronsson, (Werner, S. E., 1984) and (Larsson, G., 1999), time-series analysis and Fourier analysis method are widely applied. In the following some of the methods are applied.

The objective of the case data analysis is not to carry out a complete analysis of the data, but rather to examine if findings published in literature are also true for the Marstal case. The methods applied are chosen to match the purpose of the examination.

A second objective of the case study is to evaluate different methods for load generation, discussed in Parts 1 and 2.

9.1.1 Load to ambient temperature dependency

At the main heating plant the heat load for the system, including all loads and heat losses, is measured to the following general shape, Figure 34.

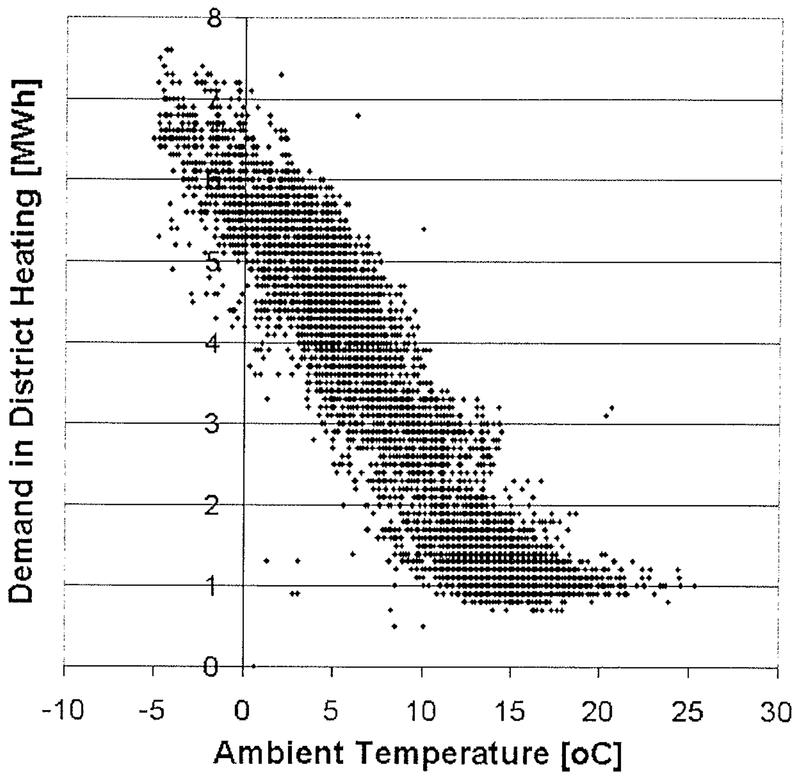


Figure 34 Heat loads to ambient temperature plot for hourly data of the Marstal district heating plant for 1998. 1997 was a very sunny year leading to a shape moved approximately 2 degrees to the right, as 1999 was very similar to the 1998 measurements. Hence the plot is representative for all collected data at the Marstal DH plant.

We see from Figure 34 that the load for the whole system is strongly correlated to the ambient temperature. According to e.g. (Werner, S. E., 1984) the correlation should consist of two linear parts. One part for the impact of the ambient temperature on the heat load, the other showing no correlation for high ambient temperature values. The first observations are supported by the findings in the figure, but the second part cannot be observed.

Due to the stepwise tendencies in the heat load dependency on the ambient temperature, a simple regression analysis cannot fit this behaviour very well. On the other hand, a stepwise linear regression would do a rather good job and therefore, the characteristic curve approach for load modelling presented in Part 1 leads to surprisingly realistic results as we will se below.

9.1.2 Load Dependency on other Meteorological Parameters

Three additional meteorological parameters are in literature examined for their influence on the heat load in district heating, solar irradiation, wind and humidity. Here a similar analysis is made on these three parameters, but with the lack of correlation, shown in e.g. Figure 35, the method does not lead to any usable model description. However, the method shows that the solar irradiation correlates stronger to the heat load than the wind speed and the relative humidity that shows similar influence on the load pattern.

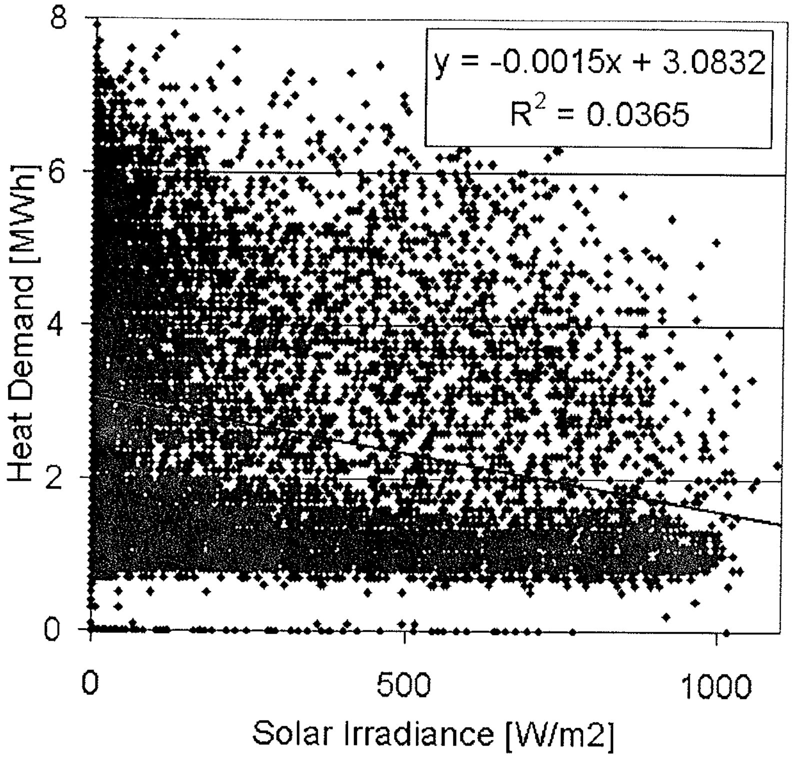


Figure 35 Plot of hourly heat loads against meteorological parameter, Solar Irradiation, for the Marstal district heating for 1997 to 1999 data. Similar plots are found for Wind Speed and Relative Humidity.

From these observations we can conclude that there is a very weak correlation between the heat load and the solar irradiation and even weaker correlation to wind and humidity. This is in good agreement with the findings by (Larsson, G., 1999) where the ambient temperature accounts for 83.1%, the solar radiation for 7.7% and the wind for 0.2%. This study adds the value for relative humidity of the same significance level as the influence from the wind. One could say that the ambient temperature is a power of 10 stronger than solar irradiation which again is a power of 10 stronger than the influence of wind and/or humidity on the heat load of central heating systems.

9.1.3 Conclusions on the Data Analysis

Based on the above examination of the measured load data of three years from the Marstal plant we can conclude the following:

In relation to the analysis methods for time series data analysis applied in literature and partly in this work:

- A number of methods are proposed in literature for the analysis of load data; 1) Simple plot analysis. 2) Simple one-dimensional regression analysis. 3) Multi-regression analysis. 4) Fourier analysis. 5) Time-series analysis.
- It was expected that the heat load in weekends differs from the workday load pattern. A plot method was applied to examine this postulate. The method proved to be very simple to use but demands a great deal of data preparation to be applicable, which would have exceeded the framework of this study.
- Due to observation of "linear" dependency of heat load to the ambient temperature, it seems obvious to apply the method of linear regression for an analysis of load data. The technique

is very simple and shows difficulties in describing the multi-causal patterns of loads, even for a single parameter.

- For multi-causal, multi-parameter analysis and model description, multi-regression method is at hand. Others reported good results. However, no attempt was made in the current work to apply this method.

In relation to the observations made in literature and this work:

- As found by (Larsson, G., 1999) the most important influence for the heat load in central heating systems is the ambient temperature, followed by the solar radiation, as the parameters for wind and humidity show to be of much less importance. In general terms one could say that the influence of the ambient temperature on the heat load is a power of 10 stronger than solar irradiation which again is a power of 10 stronger than the influence of wind and/or humidity on the heat load of central heating systems.
- Even though the plot method could show some indications on two peaks in the mornings and the evenings, no significant pattern could be found for a daily load pattern.
- No significant differences could be shown between weekends and workday loads.

All in all we can conclude that not all proposed load patterns were to be found in the Marstal data. More load data analysis would be necessary to give final theories for load modelling which is not justified by the goals set in this work. →The most important finding for the current work is that we are able to model heat loads by already existing knowledge.←

9.2 The Load Generator applied on the Marstal Case

In the current section we apply the load generator tool from Part 2 for the modelling of the Marstal district heating plant and compare the simulated load with the measured loads from 1997 to 1999.

It must be mentioned that the objective of this procedure is not to validate the generator but rather to show the application of the tool for the generation of realistic load profiles and how to do the job.

It is also worthwhile mentioning that the method of simulation is based on reference weather data. This certainly introduces a systematic difference for the heat load computed and measured data. The impact of this difference is demonstrated in (Heller, A. and Dahm, J., 1999) and is not the subject of this presentation.

Below a procedure is discussed for application and adjustment of the generation tool for a certain case. Alternative approaches will be discussed later.

Parameters are set to values known from the given plant. For the Marstal plant we know:

- the number of buildings connected to the plant are 1320.
- the buildings are mainly old single-family buildings. Hence high demand space heating load files are preferable.
- the buildings are spread over a relatively large area with low line heat demand which leads to relatively high heat losses for the system. This heat loss is estimated at 23% by the plant based on measurements. This corresponds to the estimations by (Bøhm, B., 1999b).
- the district heating network (4000 m) and the installations in the buildings are renovated in the resent years, leading to low heat losses and high efficiency for the system.
- The hot-water consumption in the summer rises to the double due to tourism.

By applying these factual values in the load generator model, we get the following picture of the load for the Marstal plant:

- The overall heat load for the plant is computed 2000 MWh too high.
- The heat loss in the DH network is only 910 MWh instead of the estimated 6000 MWh per year.
- The heat load in winter is too high and in summer too low.

As we see from these rough estimates the model must be adjusted to represent the measured load. Here lack of knowledge makes things difficult and enables many combinations of parameter sets. A few main parameters must be adjusted to get a best fit. In the current example the heat loss in the distribution system is multiplied by 7.4 of the physically true value. After the adjustment of this loss, the space-heating component is adjusted to 465 buildings with high heat demands and the rest with medium heat demands. Hereby we find the following results.

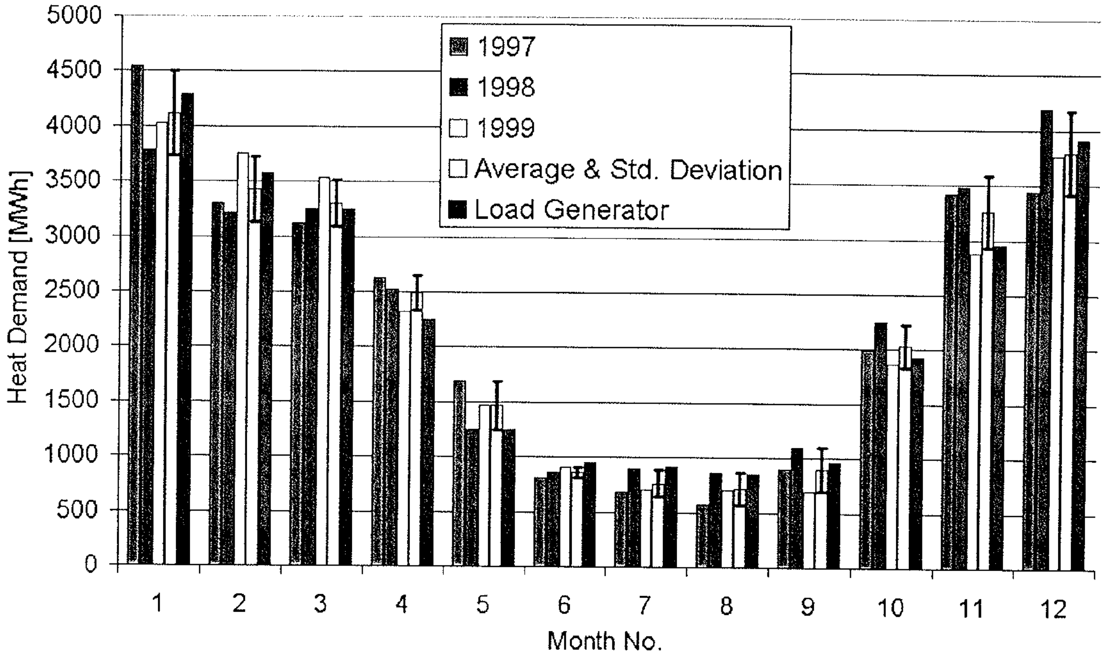


Figure 36 Monthly heat load values for the Marstal district-heating plant measured from 1997 to 1999 (left three bars). The measured average and standard deviation values for this period are plotted as the fourth bars from the left. The right-most bars show the computed values for the adjusted parameter set.

The comparison in Figure 36 shows that the heat load for the coldest winter month and the summer month are estimated rather high, as the values computed for April, May and November are too low. Such deviation can be adjusted by the model parameters. It turns out that the heat loss is of very great importance to the overall performance. Two experiments are carried out in this study: 1) A one-level approach where the heat loss during the whole year is fixed. 2) A two-level heat loss model with different circulation loss in winter and summer. The latter certainly showed the best result. For the two experiments we get a duration curve as presented in Figure 37.

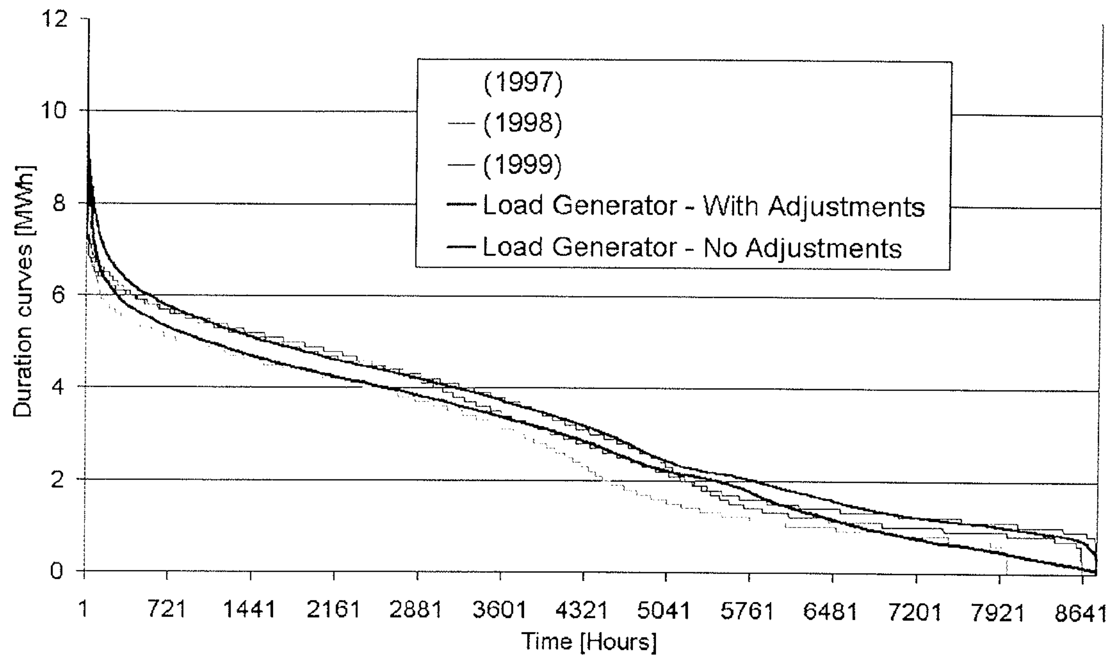


Figure 37 Duration curve for heat load measured for 1997 to 1999 and compared with two computation results: 1) "Load Generator – No Adjustments" for the computations with one yearly circulation value and hereby one single district heating heat loss parameter. 2) "Load Generator – With Adjustments" where there is circulation in non-summer periods as in 1) and a minimum heat loss in summer chosen to keep up the supply temperature at the consumers.

The duration curve for the simulations with summer and winter circulation parameters gives the best fit for the large demands but less accurate results for low heat loads. This could certainly be adjusted by choosing an even better circulation model and hereby a better heat loss simulation in the district heating.

From these results we can conclude that the heat loss model for the district heating must be chosen carefully and based on the observations at the given district heating plant.

Another subject of interest is to choose the right set of load files. It turns out that the buildings in Marstal are too old and have to high heat load to be modelled by loads generated by the Task 16 work. Hence the loads applied by (Heller, A. and Dahm, J., 1999) are used above to get a better agreement with measured data.

The last point to be mentioned here is that a procedure as the one applied is not simple to handle. Therefore a more efficient procedure must be applied to make the "bottom-up" approach a success. Here again one can apply the approach applied in Heller and Dahm, where a stochastic method is applied to find the most appropriate parameters for the model by "dynamic data fitting".

The comparison by duration curves is a very efficient tool, but the method does not take time into consideration. Hence things can be shifted in time giving a wrong result but a reasonable fit for the duration curve. Hence comparison must also be done on the time series for the computations. For the measured and the above-simulated conditions we find the following loads for the district heating system.

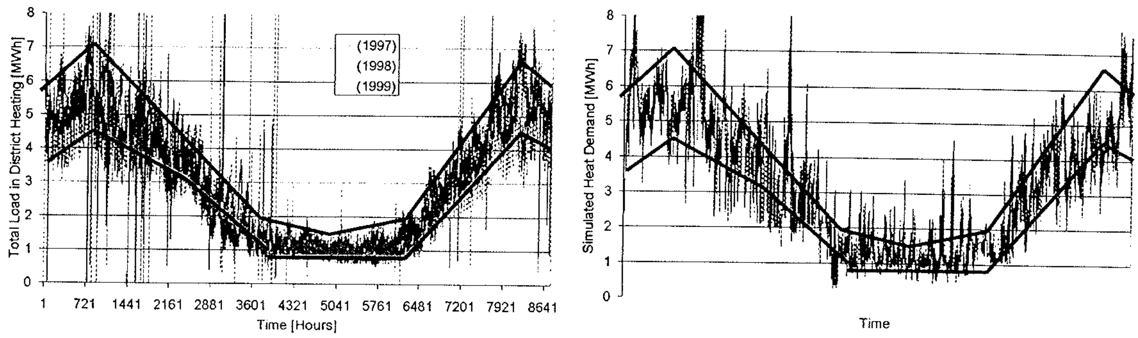


Figure 38 Measured contra simulated heat loads for the Marstal district heating plant.

Note: The thick line is to show an overall picture of the measured data. Hereby the computed values are easier to be compared.

Figure 38 shows a reasonable overall agreement between measured and computed heat load for the whole district heating system. However the fluctuations in the simulated results are larger than the measured resulting in too high and low values. The same is the case for the temperature fluctuations in the computations. This shows that the dynamic representation in the load generator, the heat load assumptions for space heating and possibly hot-water preparation, are not modelled good enough.

More discussion and conclusions will be found in the relevant section below.

10. Comparison of Methods for Load Generation

In Part 1 a number of alternative methods for load profile estimations are presented. In this section the results from these methods are compared with load profile of the above dynamic modelling approach.

The simplest model is to assume yearly and monthly values to give a rough estimate on the load. Averaging the demands would lead to the following hourly load and the corresponding duration curve in Figure 39 using average values found from the measured data of the Marstal case.

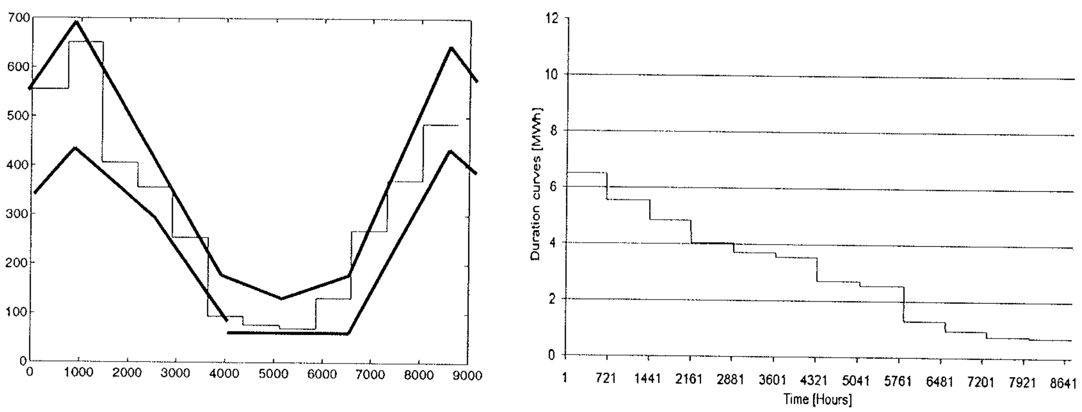


Figure 39 Hourly loads for a very simple monthly weighted load profile and the resulting heat load duration curve.

We find for the very simple method that the results are also simple, not taking any response by the system into account except from the yearly fluctuation.

The method of energy characteristics or energy signature corrects the simplicity of the foregoing method by adjusting the heat load on the ambient temperature by very simple means. To demonstrate the method the following assumptions are based on the analysis of the correlation between ambient temperature in the DRY data set and the heat load found by the load generator. It turns out that these assumptions result in much too high annual heat load. Therefore the stepwise function for the heat load is adjusted to match the yearly heat load. Based on the shape of the plot in Figure 34 we split the signature for the dependency of the load to the ambient temperature into four linear parts:

1. The maximum load is assumed for all temperatures below –12°C. Note: In Figure 34 the value is –5 degrees. On the other hand this would lead to erroneous annual heat load.
2. The dependent part where the load decreases with increasing ambient temperature from 8 MWh at –12°C down to 1 MWh at the ambient temperature of 16°C.
3. The independent part where the load is at the minimum of 1 MWh.
4. No load is observed at temperatures above 25°C. This assumptions lead to the signature shown in Figure 40.

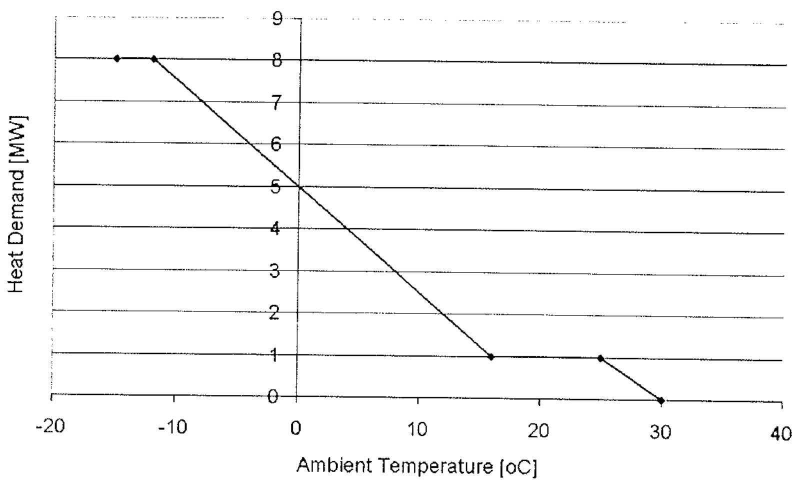
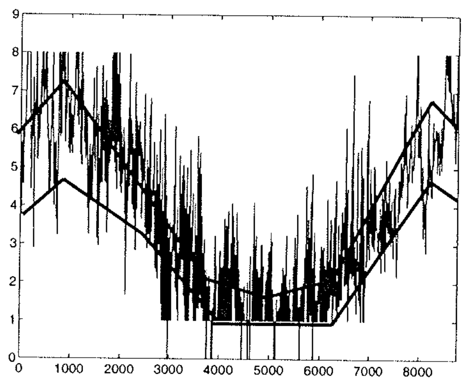


Figure 40 Assumed energy characteristics for the Marstal case.

Applying this pattern on the heat load estimation we find the duration curve as found in Figure 41.



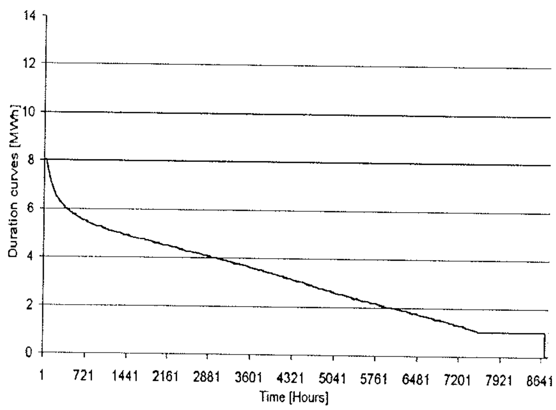


Figure 41 Heat load for the Marstal case during the year for the energy signature method (right plot) and correspondent duration curve (right plot).

We find from Figure 41 that the annual changes are computed realistically but that the values in general are too high compared with the measured values (sketched lines).

The duration curve can be adjusted by working with the signature, if necessary. It is relevant to mention that applying similar characteristic curves to other input parameters, e.g. solar irradiation, can enhance the method.

The last method that will be investigated here is based on normalisation of heat load by a simplified degree day/hours approach. The yearly degree hours for the DRY data set is 83710 hours with temperature below 17°C times the temperature difference up to this temperature. For this example we assume 25% of the heat load to be independent of the ambient temperature and 80% dependent. The load is then combined by a corrected and a not corrected part. By this procedure we find a load profile and duration curve as shown in Figure 42.

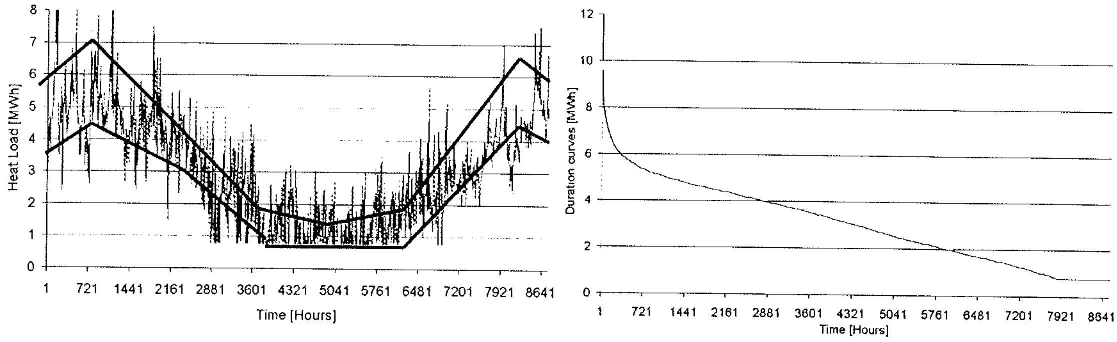


Figure 42 Heat load for the Marstal case during the year for the degree hour method (right plot) and correspondent duration curve (right plot).

The results in Figure 42 prove reasonable agreement of the computed values by the degree-day method. Similar to the dynamic method of the load generator tool the fluctuation of the results is larger than measured. However, this very simple method leads to surprisingly realistic results!

This is confirmed when comparing the duration curves for the different methods in a single plot. Note: The total annual heat demand for all duration curves is similar.

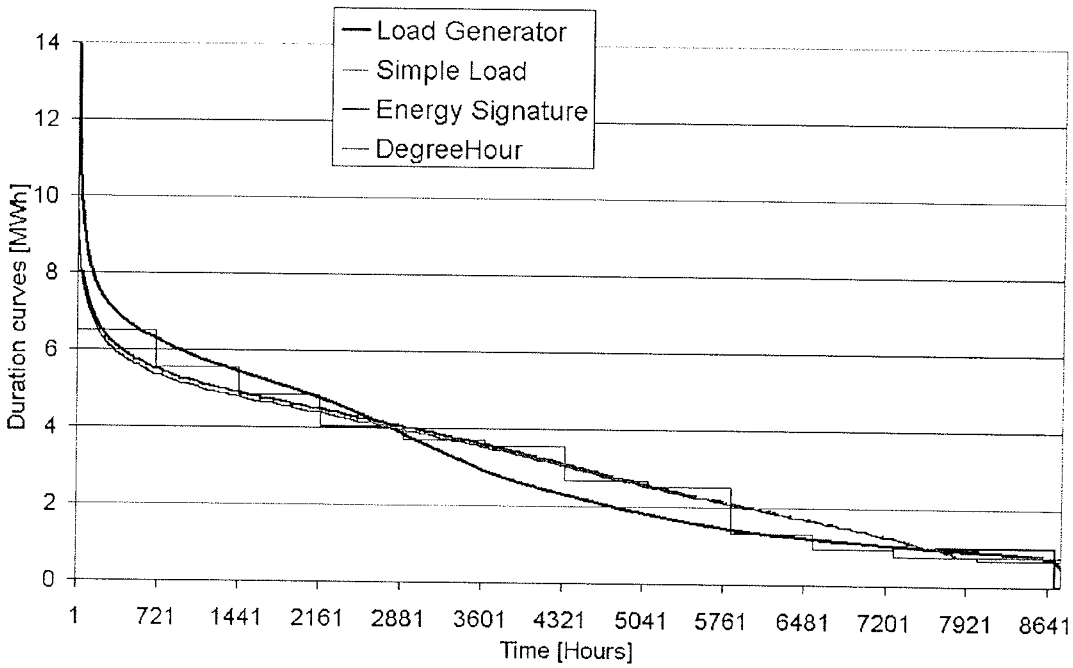


Figure 43 Comparison of duration curves found by the methods presented in this section for the generation of load profiles of central heating systems.

From the comparison of duration curves in Figure 43 we can summarise the following conclusions:

- The simple heat load model based on monthly assumptions is very simple and therefore easy to apply. The method shows a stepwise heat load and duration curve with rather poor agreement with measured data.
- The energy signature and degree-day methods show surprisingly similar results in terms of duration curves. However, the energy signature method seems to lead to higher loads than measured.
- It turns out that the profiles produced by the energy signature and the degree-day method show even better agreements with the measured data than the load generator applied in this work, even though we apply the DRY data set! Astonishing! Therefore the question comes up if it is necessary to make such a big effort to build up complex models for load generation? The answer is up to the reader and requires a long discussion presented in the final conclusion and discussion section below.

11. Case Study: Discussion and Conclusions

In this section the load generator tool is applied on a Danish district heating system, the Marstal district heating system with 1350 connected mainly single-family buildings. Other methods for the estimation of heat loads are compared.

The results found in the above are checked on the data for another district heating system in Denmark, in Hvalsø. The results found for this study were very similar to the findings above.

No attempt was made in this work to investigate the agreement between measured and modelled heat demands for short time periods. Hence findings are based on long-term comparisons only.

The comparison applied here was based on three years of measured load data and computed data based on a reference data set (not the real measured meteorological data.). This certainly introduced some errors.

We found that an approach to monthly average values cannot represent the load of a central heating system in an appropriate way and should only be applied for simple means.

We found that the two methods "energy signatures" and "degree-day normalisation" gave very similar and surprisingly best agreement with measured data. The relatively good agreement can be explained by the very dominating dependency of the heat load in central heating systems on the ambient temperature (estimated at 80% of the total load). It is worth-while mentioning that the degree-day method is not directly applicable to buildings with high thermal mass, large utilisation of solar irradiation or low energy buildings. This would be the case for the buildings of the future. Hence the method must be adjusted in coming years to be applicable to such building types. The first step to do so has already been taken by degree-day values corrected for influence of solar irradiation and wind.

Comparing the hourly results from the two above methods one finds that the degree-day approach represents the data in a more accurate way, than the method of energy signature.

The load generator did not represent the load data of the Marstal case perfectly when keeping the parameters to the physical case. This is due to lack of knowledge. Therefore the number of parameters are too high and some of the parameters must be adjusted to non-physical basis. Here the dynamic data fitting approach demonstrated by Dahm in (Dahm, J., 1999) for small district heating systemsQUOTE can be utilized.

The disagreement between the measured and the computed values for the Marstal case can be explained by the following reasons: 1) The heat load in the buildings is based on the mix of up to three load profiles. The overall load is a multiplum of the single-building load profiles. This leads to very high load peaks. Hence a stochastic distribution of the loads for the involved buildings must be adopted similar to the hot-water profile generation by (Jordan, U. and Vajen, K., 2000b). 2) The hot-water load defined by Jordan, ibid., seems to give reasonable results. For large systems, involving many users, new load profiles must be prepared to avoid peak loads. 2) The heat loss in the district heating is not only dependent on the description of the distribution network but also on the flow. Investigations above indicate that the sub-model for this circulation is very important for the overall results by the load generator. Due to lack of information on this subject this enhancement is not examined in detail in this work.

12. Discussion and Conclusions

In the current report some general aspects of heat/load demand and the modelling and simulation hereof are in focus. The main objective is to give a summarised and comprehensive overview of published knowledge in the field and to collect some of the techniques applied in the field. This is done in Part 1 of the report.

Based on this theoretical framework a load model for central heating system is implemented in the computer software TRNSYS. See Part 2 for the implementation.

In Part 3 the resulting load generator tool is applied on a district heating case and the results compared with other methods found in literature.

12.1 The Literature Survey

To describe heat loads some terms are defined in literature.

The lowest level object term is the "element" or additive elements, physically delimited objects that are additive which means that they do not correlate. As examples, heat lost in pipes, heat through a window etc. can be mentioned. The formulation claims independence between the elements, which is not the case in real world. E.g. the space-heating loads and water consumption correlate due to user behaviour. Hence the claim of independence introduces some error.

Additive elements can be collected to component models. The demand for hot water consists e.g. of the hot-water consumption, heat losses in piping and heat exchangers.

An alternative way of looking at the same thing is to focus on the common parameters, called input parameters. These parameters are used to describe the load profile without insight in the sources for heat demands. E.g. ambient temperature and solar irradiation are such parameters.

Literature in the field of heat loads in central heating systems is dominated by analysis of loads measured in real systems and here from to explain the load and correlation to different sources, parameters and so on. In this presentation this procedure is called the top-down approach.

(Werner, S. E., 1984) builds up a complex model including numerous parameters to be found by multi-regression analysis. After doing so, Werner sketches similarities between different elements and gathers them to component models.

(Aronsson, S., 1996) analyses load data to find parameters that lead to realistic representation of heat demands. The parameters are both in relation to component models and to input parameters.

Alternative to multi-regression analysis one could apply time-series analysis or neural networks to find the systematic and parameters in measured data.

Most data analyses are based on rather small data sets. Therefore results have to be taken with care. Among others, based on data analysis one author found that the space-heating demand is independent of the building area. This finding is not very realistic. The reason for such strange findings must be found in the rather small data material compared to the number of possible parameters to explain the heat load in total.

From literature study and own data analysis we find the following significance for the individual heat load components and input parameters: Space Heating is the most significant component ($\approx$ 60%), hot-water preparation ($\approx$ 10-30%) and heat losses in the district heating ($\approx$

6-25%). Less significant is the dependency of the heat load on the day in the week. For industrial district heating systems these figures are not applicable.

The significance of the input parameters to a load model shows that the ambient temperature is the absolutely most relevant parameter (≈ 83%), followed by the solar irradiation (≈ 8-10%). Less relevant is the impact of wind and humidity on the loads.

Note: The individual heat load components are discussed in detail in the report. Interested readers will be able to find some conclusions there and certainly inspiration for own work.

12.2 The Method

The method applied in the current work was to implement a dynamic model for the simulation of heat load profiles of central heating systems. The overall model is based on sub-models that are lumped mostly from load component models but also additive elements and simplified input parameter models. This method is here called bottom-up approach, opposed to the top-down approach dominating in literature. The procedure in the bottom-up approach is to describe the individual sources for heat loads more or less detailed by sub-models. The individual heat load components and elements are discussed in Part 1 in detail. The sub-models (component models) are then combined to an overall heat load model. Most sub-models are of deterministic origin, but stochastic approaches are also applied.

The final model is implemented in the computer software TRNSYS, derived in Part 2, applying a dynamic modelling approach, where the system is described by mathematical-physical equations and expressions.

In the current load model, space-heating, hot-water preparation (domestic hot water plus heat losses in circulation and heat exchanger) and heat losses in district heating are included. Thereby, according to the above authors, the most significant components should be implemented leading to realistic results.

Before the model is described, some numerical aspects of dynamic simulations are analysed and discussed in Part 2.

Some minor assumptions and simplifications had to be made in the model. A general artefact in modelling flow in pipes is called numerical diffusion. The problem is discussed in detail and examined by different computations. We can conclude from these experiments and considerations that

- All numerical techniques introduce artefacts in one or another way.
- More advanced numerical techniques reduce, or even eliminate the problem with numerical diffusion.
- It is difficult to eliminate numerical diffusion and at the same time to ensure that natural diffusion due to heat losses is still simulated realistically.
- The Cranc-Nicolson method, normally applied to flow-heat-loss problems, cannot be applied at the outlet of the pipe due to lack of knowledge. Hence wind-up difference schemes ought to be applied for these advection-diffusion problems. Quadratic interpolation schemes show minimal problems with numerical diffusion independent of the model implementation.
- The plug-flow methods show reasonable results for flow with not extremely changing boundary conditions. This is the case for large heating systems.
- Numerical diffusion is often misinterpreted as the problem occurring if the flow in a pipe is too large to be rendered by the numerical timestep. This is in a way true too, but should

rather be seen as numerical nonsense. Numerical diffusion is the artefact due to temperature changes that look like heat losses, but provoked by inappropriate choice of discretization in time and space.

- It is rather difficult to distinct between natural diffusion, which should be modelled realistically due to heat losses in the pipes and numerical diffusion. No recommendations can be given on this subject, but the reader must be aware of this subject.

In the current work, the computation of flow in pipes is the main source of numerical artefact. The pipe implementations for TRNSYS are examined and we find that the implementation in TRNSYS gives acceptable and realistic results, showing small signs of numerical diffusion. The uncertainty connected with numerical diffusion is predominated by the much bigger uncertainty due to simplification of the district heating system discussed above.

Another subject discussed in Part 2 is the simplification models for meteorological data. There are two main methods, the application of very simple regression models and the use of reference data. In the former the complexity of weather data is reduced to simple functions. Such functions are presented and discussed in this work but not applied significantly in the load simulation tool. In the latter the complexity of weather data is still kept, but the deviation between the years is collected to one single set. Two main sets of reference data are available, the Test Reference Year (TRY) and the Design Reference Year (DRY). For Danish conditions a number of data sets are available from different sources. Based on an analysis of the data sets it is recommended to use the original data sets only, to be found on the Internet-addresses: http://www.ibe.dtu.dk/forsknin/cshp/meteo/meteo.htm. Readers interested in these subjects can find a number of findings in the relevant section of the report not repeated her.

In the current work special attention was paid to the modelling of heat loss in district heating pipes. This investigation showed very large difficulties in exact modelling of this load component. One subject discussed was the question of how to find the component significance for a given case with a limited knowledge of the system only.

A good proposal is made by (Bøhm, B., 1999a). Here the heat loss is estimated on line-heat demand, which describes the load density for a district heating system to the length of the pipe. A long pipe with few connected users leads to higher heat losses than a short network with high demands.

When modelling heat losses in networks, the very complex network structure is in most cases represented by a few pipes only. The reduction of the number of pipes is proposed by a few authors and discussed in the report. Unfortunately none is mature to be applied by others at this point. Hence a very simple approach by Bøhm is recommended to be applied here. Here the heat capacity and the pipe diameter for a representing pipe-couple are estimated on the total mass of the network. The insulation level of the pipes is estimated on some simple average for the applied pipes. Hereby the total network is represented by three parameters only which can be estimated by simple, reproducible means.

12.3 The Load Generator Tool

Based on the theoretical frameworks of Parts 1 and 2, a tool for the generation of heat load profiles is derived in the computer simulation tool, TRNSYS. The tool can be applied for the generation of load profiles for central heating systems involving a number of thermal influences discussed later. The final load profiles, typically text file data sets, can then be applied by other tools for simulations. This is a main objective for the author to involve in the field of heat load modelling. In later work the load profiles are applied for the load simulation of central solar heating systems connected to district heating. The load profiles can also be applied for optimisation of central heating systems in the phases of design and operation. A realistic and detailed load description (profile) is central for such work.

The basic method in the load generator tool is to model each source for heat load by a given complexity a here called bottom-up approach. In this work, space heating is modelled by complex simulation tools. It turns out that each simulation tool has its own kind of characteristic. It is outside the current work to judge which tool leads to the most realistic loads for building. Hot-water demand is derived from a stochastic approach by (Jordan, U. and Vajen, K., 2000b). The two heat load components are then connected to the overall heat load model by text file input, multiplied to match the number of involved connected consumers of heat. The multiplication leads to peaks in loads, which are artefacts due to this procedure that is not realistic. It is recommendable to apply stochastic approaches for both space-heating and hot-water preparation to avoid unrealisticly high peak loads.

After these theoretical and numerical analyses a heat demand model is built in the simulation environment TRNSYS. The model includes space-heating and domestic hot-water consumption in the form of input files and heat losses in district heating, circulation and installation as dynamic models, controlled by parameters. The model applied reference data for meteorological parameters, for the Danish case the Design Reference Year. The space-heating input data is also generated by very complex dynamic TRNSYS-models based on work done in the (IEA SHC Task 26, 1999). The domestic hot-water consumption for up to 32 individuals is generated on stochastic theories by work in the same IEA co-operation.

This approach is chosen to utilise the very detailed knowledge of the sources for heat load demands and hereby to base a given load estimation on knowledge more than on regression assumptions. Unfortunately, as shown for the case in Part 3, the bottom-up approach gave less accurate results than other approaches based on the top-down approach. Also simulation with such tools as the current load generator gives countless possible combinations of parameters to be chosen between, which is rather demanding and difficult. This difficulty can be handled by different means, among others dynamic data fitting.

12.4 The Case Study

The district heating of Marstal with 1320 connected consumers and an annual heat load of 27,000 MWh is studied in this work. Based on three years of measured hourly heat load, supply and return temperatures in the system, a number of load models are compared and findings in literature examined.

12.4.1 Data Analysis

In literature the significance of input parameters on the heat load is discussed. In general a good agreement is found for the Marstal case. The ambient temperature accounts for the main load part followed by solar irradiation, which is a 10-potents lower in impact on the total load. The influence of wind and humidity has similar impacts that are a 10-power lower than the solar irradiation. This is the case for the load generator applied in this work.

The significance of the load components on the overall heat load is also discussed in literature. The findings by this work support the findings by others that the space heating is the dominating heat load (≈60%), followed by hot-water preparation (≈30%) and heat losses in the distribution network (≈10-30%). Weekday dependencies could not be shown for the Marstal case and are not included in the load generator tool, except for the hot-water consumption. Heat losses in district heating are in general simplified too much. (Bøhm, B., 1999a) proposes a more realistic alternative to a single value for the heat loss that describes the heat loss based on the line heat demand for the system. This term describes the density in the system dependent on the length of the pipe. Long pipes with low demands lead to higher heat losses. In Denmark the line heat demand is rather small resulting in high heat losses compared to other countries.

12.4.2 Load Simulation

In this work, a number of methods are applied for the load generation of the Marstal case in Part 3. Four methods are compared: 1) A Simple Average Method. 2) Energy Signature / Characteristic Method. 3) Degree-Hour Method. 4) Dynamic modelling with the load generator tool.

From this investigation we can conclude that the degree-hour method leads to the most realistic results if there is no detailed knowledge of a central heating system. If it is possible to correct an actual case by measured degree-hour corrections, as proposed by origin authors of the method, this should be done. If there is no knowledge of the actual degree-day or degree-hours for a given year, the following approach is recommended combining the degree-hour method with the simple monthly factor method: 1) Multiplying the annual load by monthly factors to find the monthly load. 2) Using the monthly loads for degree-hour computations.

Re 1) The simplest method using monthly average data for the load leads to stepwise results not reproducing reality sufficiently. Therefore the method is not recommendable for load modelling. As we will se, other methods are similarly simple and lead to much better results.

Re 2) The energy signature method applies functions to correlate the load on a parameter, such as the ambient temperature. The method results in surprisingly realistic load profiles, but in rather high return temperatures from the district heating. The method can be advanced to involve more than a single input parameter dependency and also apply complex functions.

Re 3) The degree-day method introduces a threshold temperature at which no heat is necessary. This is the case for space heating but not for hot-water consumption. Therefore the method includes one ambient temperature dependent part and one independent part for the total load. The dependent part is linearly correlated to the load. The method shows the best results for both load profile and return temperature and will be applied in the following work by the author due to its simplicity.

Re 2 and 3) The two above methods show surprisingly good agreement with measured data. Due to the fact that the two methods only apply a correlation to the ambient temperature, the reason for the success of these methods must be found in the very dominating influence of this input parameter. However, this appears surprising to the author.

Re 4) The implementation of a dynamic modelling and simulation method is one of the main objectives of this work. The method is implemented in the above-mentioned TRNSYS tool. The expectations were big to build a realistic load generator tool. It turns out that the method is very complex to handle and that the results are not better than the results from the methods 2) and 3). Therefore the question arises if one should base load profiles on simple and understandable methods or complex dynamic modelling?

In most cases the answer is "yes". The simple methods are preferable if the objective of a work is to use a load realistic by a certain tolerance, or if there are missing knowledge for the modelled system, or if one is not able to work with complex and demanding dynamic modelling.

If, on the other hand, the objective of a given work is to understand and investigate a certain system in detail, the answer to the above question is "no". In this case there are two methods, the "top-down" and the "bottom-up" methods. The "top-down approaches" discussed in literature showed rather large difficulties with answering questions about loads and explaining them, even though rather large efforts are made. No final theory or load model is based on these regression analysis procedures known to the author. (This is not really true because the energy signature and degree-day methods are such examples.) Dynamic modelling and simulation is therefore the only way to go, possibly combined with some "top-down" modelling for unknown heat load sources. Dynamic simulation can apply either deterministic or stochastic models or combinations. Applying deterministic models, based on physics etc., leads to very well understood models, but also leads, as we find in our case, to very complex sets of parameters not always easy to determine. If this problem is handled the method is superior in giving an understanding of the modelled matter.

One of the drawbacks for applying dynamic modelling is the complexity and the necessity of knowing a lot of the system and the parameter necessary to model the system realistically. Here lack of knowledge makes things difficult. However, there are methods to escape this shortcoming. One is parameter identification by statistical methods, such as dynamic parameter fitting. These methods find sets of parameters that lead to "best fits" for the computed results to a given "real result", e.g. measured data. The method was applied on the Marstal case by (Heller, A. and Dahm, J., 1999) to fit the number of buildings with three possible load profiles, as discussed in Part 2. The result was representing the case better than found in this study. Even though the two results cannot be compared, the conclusion can be that parameter-fitting methods can be very helpful to overcome lack of knowledge.

12.5 Conclusions on Dynamic Simulation of Heat Loads

The case study in Part 3 shows severe difficulties in getting simulations to produce realistic load profiles. A number of results support this finding.

Computed loads and temperatures are changing too strongly for the computed results compared with measurements. This can be due to measurement uncertainties or simulation uncertainties. The latter is assumed to be the case here. The conclusion here must be that the model is either not taking all relevant influences into account, or the influences are not modelled realistically enough.

The case study proved that the heat loss model for the district heating system must include not only the network and related heat losses but also a realistic flow model. It was shown that a single value for the minimal circulation in the network gives no realistic heat loss estimations for the district heating. The alternative to applying one value for the summer period and one for the rest of the year did a better job but is still not realistic enough.

Simplification methods for district heating networks and thereby the heat losses are still not developed to an applicable level. Therefore models applied in load estimations involve rather large uncertainties. To avoid unrealistic results parameter fitting techniques should be applied to find network parameters and flow parameters.

The case study showed that space-heating loads, derived by different sources and discussed in Part 2, lead to systematically different results and must therefor be chosen carefully. Here duration plots can be a very good tool to choose the right load profile. It makes no sense to choose a load profile for a futuristic building to model an existing building. This gets even more distinct when finding loads on passive solar buildings and such advanced housings where the ambient temperature is not dominating in the same magnitude.

One problematic subject that must be faced by modellers is the large number of consumers connected to the central heating system. Multiplying a single-user load profile by a large number of users leads to unrealistic peaks. To avoid this problem, (Jordan, U. and Vajen, K., 2000b) propose a stochastic deviation of loads. This is done by Jordan for the hot-water consumption. Load profiles for single-family, and up to 32 consumers are generated and proved to lead to very realistic load profiles.

For large systems as central heating systems, the load profiles of 32 persons could not avoid all peaks. Hence it is recommendable to generate even larger load profiles for up to 1000 households in one single load profile for this purpose.

Space heating involves similar problems with peak-loads as described for the hot-water case. The result of multiplying a single load for many consumers leads to the unrealistic peaks as found for the load generator in Part 3. Therefor it is necessary to apply similar stochastic distribution procedures as proposed for hot-water consumption by Jordan (ibid.) for the generation of space-heating loads.

The Marstal case shows severe problems with determining realistic parameters for the overall model. This is due to lack of knowledge and due to the amount of freedom in the system, which leads to many possible combinations of parameters, leading to similar results. It was not possible to derive a successful procedure to find such parameters in the current work. Therefore it is advised to utilise statistical methods for this purpose as demonstrated (Dahm, J., 1999) and (Heller, A. and Dahm, J., 1999), applying dynamic parameter identification or by applying optimisation methods.

13. "POSTFACE"

It was the idea of this work to be able to propose a load generator model. This goal has not been obtained. Hereby I am lining up in the long row of scientists to describe heat loads. From this point of view it is not surprising that the goal was not obtained. However, here are some comments on this failure:

It is the belief of the author that with the proposed improvements in district heating flow modelling, hot-water preparation and space heating, one would be able to get much better results as demonstrated in this work.

It is also my belief that dynamic simulation can be a tool for the study, understanding and optimisation of central heating systems in the phase of design and operation that goes beyond data analysis.

A very important subject in relation to the application of dynamic modelling that brings us much above the current work is the demand for optimised systems. This need is pronounced by the fact that non-optimised engineering has produced many serious problems for the mankind in the form of environmental problems and exploitation of natural resources. Optimising systems requires better understanding of the matter to be optimised. In many cases optimised systems show stronger dynamic behaviour that is not caught by simple methods. Hence more advanced methods are necessary. In both cases dynamic modelling and simulation is a cheap and powerful tool. Therefore the answer whether to apply the load simulation tool is "yes" if we aim at making optimised systems.

14. NOMENCLATURE

Greek:

A	helping value
A	matrix
B	helping value
C	distance between the pipes in metres
C_e	heat capacity of the element (pipe and fluid) in J/(m K)
C_n	n'th coefficient in Fourier solution for ground temperature
C_p	heat capacity of water in J/(kg K)
Cou	Courant-number
D_c	outer diameter of the pipe casing in m
D_e	outer diameter of the pipe casings in m
GD	degree-day value
GH	degree-hour value
I_b	beam solar irradiance in kWh/m^2a
I_d	diffuse solar irradiance in kWh/m^2a
L	length in m
M_b	mass flow rate through the bypass in district heating system in kg/h
M_h	mass flow rate through the user installation (house) in kg/h
M_p	mass flow rate at the plant in kg/h
$\dot{M}_{sh,ist}$	objective mass flow rate in kg/h
$\dot{M}_{sh,soll}$	demanded mass flow rate in *kg/h*
N	number of observations corresponding to the time unit or the periodic of the cosine function
N	total number of time-steps for the simulation interval
N_{year}	number of seconds in a year
Q	heat load in W
$Q_{l,r}$	heat loss in the return heat pipe in W
$Q_{l,s}$	heat loss in the supply heat pipe in W
$Q_{l,tot}$	heat loss in the distribution heat pipe net in W
R_g	thermal insulance for the ground in m^2 K / W
R_h	thermal insulance between the two pipes in m^2 K / W
R_i	thermal insulance for the insulation material in m^2 K / W
$R_{\alpha e}$	surface thermal insulance at the pipe case surface to the ground in m^2 K/W
R_0	surface thermal insulance of the ground surface, normally set to 0.0685 m^2 K /W
T_a	ambient temperature in °C
$\overline{T}_a$	mean temperature over the given period in °C
$\overline{T}_a$	mean cold water temperature over the given period (year) in °C
$\hat{T}_a$	amplitude of the variations over the given period in °C
T_{cw}	cold water supply temperature in °C
T_g	ground temperature in K, which under code conditions is 8.8°C
$T_{g,x}$	undisturbed ground temperature in °C
$T_{h,soll}$	demanded hot supply temperature in °C
T_i	inlet temperature in °C
T_i	temperature of i'th element in the pipe in °C
$T_{l,soll}$,	demanded hot supply temperature in °C
T_s	supply temperature from district heating plant in °C
T_{s0}	supply temperatures at the plant in K

T_s'	supply temperature to the building in °C
$\overline{T}_s$	average temperature of the supply pipe line in K
T_r	return temperature at the plant in °C
T_{r0}	return temperature at the plant in K
T_r'	return temperature at the consumer in °C
$\overline{T}_r$	average temperature of the return pipe line in K
T_o	outlet temperature in °C
ΔT_h	temperature difference over the building connection in K
ΔT	temperature difference in K
$\overline{T}$	mean temperature in °C
U_1	heat transfer coefficient from DH pipes to surroundings in J/(m K)
U_2	heat transfer coefficient between the two DH pipes in J/(m K)
U_p	heat loss coefficient of the pipe in W/(m K)
V	mass flow rate in kg/s
Y	dependent model variable
X	independent model variable element
Z	corrected depth of the piping in m

c_p	specific heat capacity in kJ/(kg K)
$c_{p,g}$	specific heat capacity of the ground material in kJ/kg K
d_y	diameter of the steel pipe in m
e	error
f'	first derivative of the function f
$f(x)$	initial condition
$g(t)$	boundary condition
i	step counter in the time domain
k	advection parameter describing the flow characteristics
l_i	the length of the i'th element in the pipe in m
m	counter in the space domain
$\dot{m}$	mass flow rate on kg/s
n	counter in the time domain
n	counter
s	mass flow ratio between the mass flow through the house installation and the total flow in the DH
t	time in s
u	dependent variable
u_o	conditions for the pipe surroundings
$\widehat{u}_i^m$	computed value for the grid point (i,m)
u_i^m	"accurate" value in a grid point
x	position in space in m
x	position along the pipe in m
x	dependent variable
z	physical depth of the piping in metres

Roman:

Δ	difference
Δx	step lengths in the space domain
Δt	step length in the time domain
Φ	function of one or more variables
$O(\delta^{t})$	remainder when restricting the Taylor series to a certain number of terms
α	thermal diffusivity for the pipe material in m^2/s
α_g	thermal diffusivity of ground material in m^2/s
β	model coefficients
β	helping value in m^{-1}
λ_i	thermal conductivity or the insulation material in m K / W
λ_g	thermal conductivity or the ground in m K / W
κ	coefficient in ground temperature computations in m
θ_s	difference temperature between ground and outlet of supply DH pipe in K
θ_r	difference temperature between ground and outlet of return pipe in K
τ	time in a given unit
τ_c	time for which the minimum value is obtained, same unit as time
τ_c	time where the coldest temperature of the year occurs
τ_s	time for which the maximum value is obtained, same unit as time
ρ_g	density of the ground in kg/m^3
δ_n	n'th coefficient for Fourier solution for ground temperature
μ	substitution variables

Indices:

p	actual period for the degree day method
n	normal period for the degree day method
sh	degree day dependent part
i	number of the actual element (1,2,..,n)
n	total number of independent elements that shape the dependent variable
g	ground
i	insulation

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